Custom Mechanisms for Tunable Material Deposition

by

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Abstract

Digital fabrication tools, specifically additive manufacturing systems, have consistently advanced in efficiencies such as print speed, gantry size, material cost and ease of use. However most of these systems remain limited in their ability to enable automated mixing and extrusion of multiple materials with variable properties on large scales. This thesis focuses on the first steps of realizing this enabling technology by operating across two distinct trajectories. The first aims at digitally controlling precision path placement of material with high levels of tunability through analog mixing, while the second explores do-it-yourself tool customization, compactness, portability and the possibility of fabrication node-to-node communication. Inspired by the silk-worm’s ability to spin highly sophisticated and tunable material architectures, the aim of this thesis is to develop an enabling technology for digital fabrication requiring high levels of material tunability in product and architectural scales. Specifically, I designed, developed, built and evaluated an array of six unique customizable and compact deposition heads for tunable material properties. Amongst those tools is a freeform extrusion head for tunable geometry without the need for auxiliary support structure; a fast thread deposition head and a fiber winding head for tunable compressive and tensile strength respectively; a portable cable-suspended paste droplet extrusion head for tunable drop size of paste material; and a chitosan gel extrusion head for tunable plasticity using biomaterials. Operating across the two trajectories of tunability and portability, this thesis argues that highly tunable, compact and portable extrusion heads developed within a Fab Lab environment can support variable property printing of one or more materials outside of commercial based systems. This capability will in the future enable the digital fabrication of larger-scale prototypes, sustainable products and architectural structures inspired by nature in Fab Lab settings.

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Chapter 1

Introduction

To date, digital fabrication systems have typically functioned as manipulators of pre-defined materials. This has typically been the case in subtractive capacities, but also more recently in additive manufacturing systems. With the introduction of Computer Numerically Controlled (CNC) machining in the 1950’s [Reintjes, 1991] digital computing became associated with physical machine control. However, the digital revolution that followed did little to integrate between Computer Science and the physical sciences. Furthermore, given that the control of motors and the various elements of the tooling process remain an analog process, the notion of “digital” must be challenged in the context of physical matter and the design of hardware [Gershenfeld, 2005].

Most recently, Three Dimensional Printing (3DP) has evolved to provide increased precision control over material placement by digitally controlling droplet position in space via the computer. However, the mode of droplet placement is still an analog process [Gershenfeld, 2005]. Some of the most innovative research done in this area comes from the Center for Bits and Atoms (MIT) and the Creative Machines Lab (Cornell University). Under the umbrella of “Digital Materials”, research at the CBA has previously presented analogs to atoms and bonds that enable the allocation of individual elements within a physical structure “much like the encoding of a data structure” [Popescu et al., b]. In this work, experimental measurements are presented that show how this control is used to tune both mechanical and elec-
tronic material properties and, in addition, it demonstrates how to implement the generation of assembled functional structures [Ibid]. This research challenges current additive fabrication approaches by considering digital materials that are defined as discrete and non-continuous physical voxels referred to as Digital Materials [Gershenfeld, 2005, Popescu et al., b, Popescu et al., a, Hiller and Lipson, 2007, Hiller and Lipson, 2008]. While this thesis does not aim at replicating digital materials, it builds off of the notion that this approach enables precise control of property variation in a predictable and logical way without distinguishing between the digital and physical domains. The aim of this thesis is to demonstrate a deeper understanding of digital control of continuous materials through analog mixing of different material properties in a non-commercialized format, supporting a fab-lab like environment. My work is inspired and informed by the "maker movement" which facilitates the spirit of tool making, that of designing computers that do not control other tools but rather computers that are tools in themselves, and, eventually building "Machines that make Machines" [Gershenfeld, 2005, Gershenfeld, 2008, Gershenfeld, 2009].

In contrast to digital materials, the state of the art in Digital Architecture focuses on fabrication as assemblies of prefabricated low-level components that are materially homogeneous [Oxman and Mitchell, 2010]. The established approach of constructing pre-manufactured building components stands in contrast to the potential of digital fabrication systems to deliver highly customized structural and material forms. In the biological world, however, there exist various organisms able to deposit highly sophisticated material architectures to construct large-scale and highly efficient structures.

The Bombyx mori silkworm, for example, varies the chemical composition of its silk according to the desired function. In this respect the silkworm can be considered a portable organism able to extrude highly tunable material architectures [Oxman et al., 2012a]. Inspired by the silkworm, this thesis sets forth a framework for the classification of digital fabrication systems - specifically, additive manufacturing - along two main axes: the first axis is that of material tunability ranging from "primitive" non-tunable and homogeneous material architectures to sophisticated tunable and heterogeneous ones. While the ability to achieve and control Digital Materials as
per CBAs definition, where parts can potentially code for the structure of the building, is not yet implemented, my research in this context points towards this capability and its promise. Inspired by the notion of the Fab Lab, the second axis is that of tool compactness and portability ranging from stationary non-portable tools (like a typical 3D printer) to highly compact and portable systems (like the silkworm itself).
Figure 1-1: Research framework: at the core of this thesis is the assumption that additive manufacturing systems will advance along two trajectories. The first is material sophistication, through tunable material properties and the ability to co-extrude fiber composites. The second is compactness and portability of fabrication devices. This matrix provides for a research framework within which the designs of 6 extrusion heads is implemented and tested.

The thesis is organized in two main chapters. The first (Chapter 2: Compact & Tunable Material Deposition in Nature) reviews the method by which the silkworm extrudes silk and what are the parameters that govern the geometrical and physical tunability of the fiber on various scales. The second (Chapter 3: Compact & Tunable
Material Deposition in Digital Fabrication) offers an array of compact extrusion heads that I designed, developed and evaluated in the context of specific design projects. The following sub-sections (1.1-1.6) offer a short description of the main chapters, their content and structure.

1.1 Compact & Tunable Material Deposition in Nature

The formation of highly tunable non-woven fiber architecture generated by the *Bombyx mori* silkworm is investigated as a case study for tunable extrusion in the biological world. Beyond the analogy of the silkworm as a highly portable organism for tunable material deposition, this section also suggests that the silkworm’s method of depositing silk can provide for a computational approach for shape and material optimization as well as, potentially, material fabrication. Biological case studies are presented and a design approach for the use of silkworms as entities that can compute and fabrication fibrous material organization is given in the context of an architectural design installation. The chapter demonstrates that in the absence of vertical axes the silkworm can spin flat silk patches of variable shape and density and therefore, the spinning behavior can be template and tuned by providing the silkworm with topographical constraints. Furthermore, experiments presented in this section suggest sufficient correlation between topographical surface features, spinning geometry and fiber density. The chapter represents a scalable approach for optimization-driven fiber-based structural design and fabrication, and suggests a biology-driven strategy for material computation and deposition towards possible applications in digital fabrication.
1.2 Compact Freeform Extruder Head for Tunable Geometry

Freeform 3D Printing: Towards a Sustainable Approach to Additive Manufacturing

This section is the first of a series of sub-sections to be included under chapter 3: “Compact & Tunable Material Deposition in Digital Fabrication”. This section presents a compact freeform extruder head for tunable geometry.

Most additive manufacturing technologies such as 3D printings utilize support materials in the fabrication process. Beyond the technical challenges of support removal, these materials are wasteful increasing fabrication and processing time while impacting quality. This section presents “Freeform Printing”, a novel design approach for 3D printing without additional auxiliary structures. A 6-axis KUKA robotic arm is repurposed as a 3D printing platform onto which custom-designed thermoplastic extruders are attached. Freeform extrusion using a round nozzle attached to an active air-cooling unit, which solidifies the material upon extrusion is demonstrated. In addition, a method for printing geometrically complex structures using a multi-strand extrusion nozzle is presented. The experiments presented in this section, combined with their evaluation and analysis, provide proof-of-concept for Freeform Printing without support materials. They represent a sustainable approach to additive manufacturing and digital fabrication at large, and point towards new possible directions in sustainable manufacturing.

1.3 Compact Fiber-pulling Head & Fast-thread Deposition Head for Tunable Fibrous Compressive Strength

Robotically Controlled Fiber-based Manufacturing as Case Study for Biomimetic Digital Fabrication
This section presents a compact fiber-pulling head as well as a fast-thread head for tunable fibrous compressive strength.

The research explores the process of silk deposition generated by the silkworm *Bombyx mori* and proposes a novel fiber-based digital fabrication approach inspired by its biological counterpart. I review a suite of analytical methods used to observe and describe fiber-based constructions across multiple length-scales. Translational research from biology to digital fabrication is implemented by emulation in the design of fiber-based digital fabrication techniques utilizing a KUKA robotic arm as a material deposition platform. The methods by which the silkworm *Bombyx mori* constructs its cocoon and scaffolding structure is discussed, and possible applications of fiber-based digital fabrication in the construction of an architectural pavilion as a case study are speculated upon.

### 1.4 Compact CNC Fiber Placement Head for Tunable Tensile Strength

**Silk Pavilion: A case study in Fiber-based Digital Fabrication**

This section presents a CNC fiber placement head for tunable tensile strength, designed and deployed for the Silk Pavilion.

The Silk Pavilion explores the relationship between digital and biological fiber-based fabrication on an architectural scale. Its primary structure is comprised of 26 silk-threaded polygonal panels laid down by a CNC (Computer-Numerically Controlled) machine. Inspired by the silkworms ability to generate a 3D cocoon out of a single multi-property silk filament, the Pavilion’s overall geometry was created using an algorithm that assigns a single continuous thread across patches, providing functional density gradients informed by environmental constraints such as light and heat. Overall density variation was informed by deploying the *Bombyx mori* silkworm as a biological multi-axis multi-material 3D “printer” in the creation of a secondary fiber structure. 6,500 silkworms were positioned on the scaffold spinning flat non-woven
silk patches locally reinforcing the CNC-deposited silk structure. The section provides a review of basic research into the silkworms spinning behavior, material and structural characterization, computational simulation and fabrication strategy devised for the full-scale construction of the Pavilion. I conclude with potential applications for fiber-based digital fabrication in large scale that implement some of the insight gained from biologically-inspired fabrication.

1.5 Portable Paste-Drop Deposition Head for Tunable Compressive Strength

This section presents a portable paste-drop deposition head for tunable compressive strength. The head was designed developed as part of a cable-suspended robotic 3D printing platform. The aim of the project was to achieve high levels of material tunability using a compact and portable single-node fabrication system, and high levels of communication using a multi-node fabrication system, respectively. The extrusions unit is inspired by the Skycam technology only instead of a camera I developed and integrated a paste drop deposition head.

1.6 Compact Chitosan Deposition Head for Tunable Plasticity

This section presents work-in-progress for a chitosan deposition head for tunable plasticity. The compact chitosan deposition head was designed to achieve highly tunable fibrous material deposition for deployment under the water and controlled spatial deformation over time. My tool was developed in the context of current group work for the construction of an underwater Pavilion designed to immobilize clean seawater by deploying large-scale soft biodegradable chitosan gel structures that take on their morphology when submerged within the ocean’s surface. The extrusion head was designed as a two-chamber head containing chitosan (semi-viscous material) while
a second chamber would enable storage and dispensing of granular material based upon the filler requirements for tunable plastic properties.
2.1 Introduction

2.1.1 Form-generation and Optimization in Nature

Biological systems can be characterized as entities that “compute” and “fabricate” material organization according to external performance criteria. Bone tissue, for instance, alters between states of compact tissue and spongy tissue as a function of the applied structural load and the requirement for blood circulation [Oxman and Mitchell, 2010]. Similarly, spider silk alters its mechanical properties as a function of its use: spiral silk is used for capturing prey while cocoon silk is used for protective egg sacs [Nova et al., 2010]. The range of variation in material distribution and physical properties is typically defined by the extreme set of external conditions acting as the “environment”. The system’s overall form and mechanical properties are derived from processes of shape and material optimization respectively, maximizing compatibility between the system’s innate material properties, its external environment and its desired performance criteria [Oxman et al., 2012c]. As a result natural systems typi-
cally exhibit high levels of integration between shape, structure and material making Natures designs highly efficient and effective forms of “computation”.

Furthermore, going beyond the already absent examples of complex materials that insects and animal in nature secrete for their various purposes, speculative fiction has often extrapolated this capability to interesting and intriguing new heights eg. [Forward, 1996].

2.1.2 Form-generation and Optimization in Digital Design

Unlike the biological world in which there exist high levels of integration between shape and material distribution [Benyus, 2009], digital design protocols are typically divided into processes of form-generation and processes of performance-based optimization, the former being a precondition for the latter [Oxman and Mitchell, 2010]. Finite element methods for example, implemented in order to optimize shape, material properties and distribution, are applied only after the form has been generated [Brenner and Carstensen, 2004]. Another distinction between biological and digital optimization is the ability in the Natural world to produce combinations of property and morphological variation of isotropic structures [Benyus, 2009, Omenetto and Kaplan, 2010, Oxman et al., 2012a, Oxman et al., 2012b]. In digital design, optimization processes are typically divorced from material organization, since most fabrication materials are anisotropic in property [Oxman et al., 2012c]. Given the advantages of biological shape-generation and optimization protocols, can processes of biological optimization be used to inform and compute desired structural and environmental performance of man-made structures?

Given almost any 3D entity, a broad suite of techniques in computational design exists that supports form-generation and optimization processes within parametric environments [Kolarvevic and Klinger, 2008]. Examples of such techniques include particle systems, multi-agent systems, network analysis, and finite element methods [Haroun and Hanna, 2004]. Replacing such computational processes with biological ones allows informing shape-generation processes as well as spatial material organizations within a single (biological) system.
2.2 Background

2.2.1 Biological Computation for Digital Design & Fabrication

Numerous forms in Nature achieve their shape and structure through local optima processes, as material organization and composition are informed by structural and environmental stimuli [Brady, 1985, Colorni et al., 1996]. Consider the optimal shape of tree branches or animal tissue morphology. These shapes and their material composition express an effective use of information as well as an efficient thermodynamic operation for an environment-interacting system. These processes can be used both as models by which to explain and predict other natural processes but also as computations in their own right [Brady, 1985, Colorni et al., 1996, Shaffer and Small, 1997].

Research into the use of biological processes as forms of computation that can inform design generation are found for example in the use of slime molds in order to model real-world infrastructural networks [Tero et al., 2010]. Here problems are described as instances of the distributed growth dynamics of the slime mold resulting in the encoding of a general linear programming (LP) language. Results prove that the model converges to the optimal solutions of the LP [Ibid.]. Captured in a biologically inspired mathematical computation, this research can potentially guide network construction in other domains.

2.2.2 The Silk Pavilion - General Background

Inspired by optimization processes in Nature like that of the slime mold described above, the Silk Pavilion is an architectural structure fabricated by digital fabrication technologies combined with the deployment of live silkworms. It explored the relationship between digital and biological fabrication on product and architectural scales. The primary structure is created of 26 polygonal panels made of silk threads laid down by a CNC (Computer-Numerically Controlled) machine. Inspired by the silkworm’s ability to generate a 3D cocoon out of a single multi-property silk thread
(1km in length), the overall geometry of the pavilion is created using an algorithm that assigns a single continuous thread across patches, providing various degrees of density. Overall density variation is informed by the silkworm itself deployed as a semi-stochastic biological “printer” in the creation of the secondary structure. A swarm of 6500 silkworms were positioned at the bottom rim of the scaffold spinning flat non-woven silk patches as they fill the gaps across the CNC deposited silk fibers. Following their pupation stage the silkworms are removed. Resulting moths can produce 1.5 million eggs with the potential of constructing up to 250 additional pavilions (Figure 2-1).

Figure 2-1: Composite image of completed Silk Pavilion installation and *Bombyx mori* silkworms spinning on the CNC fabricated super-structure.

Affected by spatial and environmental conditions such as geometrical density gravity [Chen et al., 2012], variation in natural light and heat the silkworms were found to migrate to denser and darker areas. Desired light effects informed variations in material organization across the surface area of the structure. A season-specific sun path diagram mapping solar trajectories in the space dictated the location, size and density of apertures within the structure in order to lock in rays of natural light entering the pavilion from South and East elevations. The central oculus is located against the East elevation and may be used as a sun-clock.
The construction process of the Silk Pavilion was inspired by basic research experiments reported herein that informed processes of modeling, analysis and fabrication. This section reports upon experimental work considering biological forms of computation for digital design modeling, analysis and fabrication. Specifically, we explored the formation of non-woven fiber structures generated by the *Bombyx mori* silkworm as a computational schema for determining shape and material optimization of fiber-based surface structures particularly because it is the most common species found for silk production when compared to the various wild species[Chen et al., 2012]. This biological form of “computation” can potentially exclude the need for Finite Element methods.

### 2.3 Aims and Goals

Fiber-based structures are ubiquitous in both architectural and biological systems. Robust structural performance involves the balancing of force-and-response in order to achieve material morphologies that are structurally efficient and environmentally effective [Oxman et al., 2012c]. Typically this process involves a step-wise process including computational modeling, finite-element analysis and digital fabrication. Biological fiber-based structures such as the silkworm’s cocoon however may provide for the unification of these three media through the use of the silkworm’s path as an optimization “tool-path” and a fabrication “technology”. The guiding assumption here is that the silkworm’s ability to generate fiber structures with varying degrees of density based on its environment has been perfected through evolutionary pressure. It is also assumed that the cocoon is an optimal structure which itself is based on the idea that optimization-seeking processes are omnipresent in Nature. Having been developed without top-down control this case may represent a scalable approach for fiber-based structural design based on optimization. Our main goal is to determine whether these structures are likely to yield reasonably efficient solutions to combinatorial optimization challenges such as load informed fiber-density distribution in membrane structure.
2.4 Methodology and Experimental Set-up

The experimental set-up consisted of a series of surface patches measuring 80x80mm in surface area with varying sectional configurations. A live silkworm was positioned on top of the surface and left to spin. It is hypothesized that spinning configurations and the fiber density distribution would vary according to the morphological features of the hosting "environment" (Figure 2-2).

![Placement of a Bombyx mori silkworm on top of a flat surface-spinning platform.](image)

Figure 2-2: Placement of a *Bombyx mori* silkworm on top of a flat surface-spinning platform.

2.4.1 Initial Experimentation to Determine Fiber-Density Variation in Flat-spun Silk

The first experiment consisted of a flat surface patch with no additional surface features. The silkworm appeared to have spun a flat silk patch instead of the anticipated 3-D cocoon structure. This was due to the lack of a physical vertical pole/axis against which the silkworm would otherwise construct its cocoon. The experiment confirmed that the *Bombyx mori* silkworm would spin silk as a flat patch in the absence of vertical surface features (Figure 2-3).
Figure 2-3: A *Bombyx mori* silkworm completing the deposition of approximately 1km of flat-spun silk. The research confirms that given the absence of a vertical axis the silkworm will spin a flat silk patch

2.4.2 The Dice Series

Following, a central vertical axis of varying heights was introduced to determine (1) at which height point would the 3D cocoon structure emerge, and (2) how might fiber distribution be affected by the relative location of the vertical axis and its height. A family of tent-like structures consisting of a rectangular surface patch with a single vertical axis ("1-dice section" per Figure 2-4) was set up.
Figure 2-4: Comparison of two 1-dice configurations with a 3mm and a 21mm vertical axis illustrating the difference between flat spinning (sufficiently short vertical axis) and a cocoon spinning (sufficiently long vertical axis).

Varying axes heights of 3mm, 6mm, 9mm, 12mm, 15mm, 18mm, 21mm, 24mm, and 27mm were implemented (Figure 2-5).

Figure 2-5: Series of one-dice platforms ranging in vertical axis height from 3mm to 27mm each with 3mm increments.

The experiments demonstrated the following: (1) a 3D cocoon structure emerged only at a sectional height of 21mm height below which a tent-like structure in the form of a rectangular pyramid was spun. Given the dimensions of the natural cocoon it was assumed that a minimum height of ~ 21mm accounting for the longitudinal axis of the cocoon must be provided in order for a 3D structure to emerge. In the absence of this height, a non-enclosed surface patch will be spun; (2) fiber density typically varied as a function of the distance from the central vertical pole to the surface boundary. This may point to a local optima condition requiring the least amount of energy for the construction of a strong stable structure within a given timeframe (Figure 2-6); (3) boundary contours were typically denser. It was assumed
that this is due to the silkworms constant search for a vertical pole tall enough to allow for cocoon construction.

Figure 2-6: 18mm one-dice platforms illustrating higher density deposition along the shortest distances from the geometrical center to the surface boundary contour.

Additional experiments followed exploring in-depth relations between topographical surface features and fiber density. These include the Rectangular FEM-Dice Series, the Pentagonal FEM-Dice Series, the Thrust Vault Series, and the Maltese-cross series. Their descriptions are given below.

2.4.3 The Rectangular FEM-Dice Series

The series included a set of 15 flat 80X80mm surface patches in different dice-face configurations. Poles of 10-15mm height were used to define the planar configuration and the sectional height of the patch (Figure 2-7). A live silkworm was then positioned in each patch to spin a typical 1km long filament. The assumption was that the variation in fiber density and organization would reflect the morphological constrains given by the "environment" (i.e. the surface patch).
Figure 2-7: Series of (15) rectangular FEM-dice platforms ranging from 10mm to 15mm in pole heights.

FEM representations were computed as hypothetical static-force studies for anticipated fiber variation in a membrane tent-like structure accommodating the environment given by the patch. Linear Elastic Isotropic 101 Nylon with an elastic modulus of $1000000000N/M^2$ was used to represent the membrane material. The results of the study confirm general correlation between anticipated Stress-Strain calculations (computed using the Solidworks environment) and the resulting fiber-structure as spun by *Bombyx mori* silkworm. See a typical example in Figure 2-8.
Figure 2-8: 4-Dice face configurations. L to R: Digital representation of anticipated stress for membrane structure based on 4 poles calculated within Solidworks; physical model with digital representation as base. The silkworm is shown to the right; physical model juxtaposed with silk fiber by the *Bombyx mori* silkworm. Denser fibers appear between poles along boundaries as anticipated by the FEM model.
2.4.4 The Polygonal FEM-Dice Series

![Series of polygonal FEM-Dice platforms.](image)

The results of the study confirm general correlation between anticipated Stress-Strain calculations (using the Solidworks environment) and the resulting fiber-structure as spun by *Bombyx mori* silkworm. See a typical example in Figure 10 below demonstrating fiber distribution along regions of highest stress around the central vertical axis of the patch in Figure 2-10.
2.4.5 The Thrust Vault Series

Unlike the two previous series, the Thrust Vault Series is comprised of non-flat 80X80mm patches varying in topographical features. Sectional height varies across 5mm and 20mm with 5mm increments; each model is repeated twice to validate the consistency of the resulting morphology. Color annotations represent variation in curvature with the color green typically representing anticlastic curvature and blue representing synclastic curvature (Figure 2-11).

The assumption was that the variation in fiber density and organization would reflect the morphological constraints given by the environment. Indeed, our results
confirm this correlation below 20mm height (above this height the 3D cocoon appeared): a typical model demonstrates increased fiber density along the boundaries. In addition, a circular patch appears at the center of the patch marking the silkworms attempt to form a 3D cocoon between the two planes that make up the section (Figure 2-12).

![Figure 2-12: 20mm tall thrust vault spinning platform demonstrating the silkworms spinning behavior.]

**2.4.6 The Maltese-cross Series**

The final series introduces variations in both plan and sectional configurations. The plan configuration in this series is no longer constraint to a completely flat rectangular, polygonal or circular surface patch but rather it is oriented in a Maltese-cross configuration. The variation in section height introduces spatial 'gaps' to the silkworm’s movement as it spins its silk in circular motion. Sectional height varies between 5mm and 20mm with 5mm increments; each model is repeated twice to validate the consistency of the resulting morphology. Color annotations represent variation in curvature with the color green typically representing anticlastic curvature and blue representing synclastic curvature (Figure 2-13).
As anticipated, the results reflect the correlation between fiber density and surface features, demonstrating a combination between the flat-dice-series and the thrust-vault series.

2.5 Results and Discussion

This work demonstrates that the silkworm *Bombyx mori* forms fibrous silk networks on flat patches. Fiber density distribution appears to be sufficiently similar to the anticipated fiber density variation that was computationally generated for a prescribed membrane structure of the same mass and surface area. In conclusion, the *Bombyx mori* silkworm itself may be used as a biological “tool” with which to “compute” fiber distribution within small-scale 1:1 structures, or as scaled representations of larger architectural structures constructed with fibrous materials.

This work is still in its early stages. The core mechanisms required for fibrous network formation can be further captured within a biologically inspired mathematical model that may be useful for anticipating fiber density and organizational variation in fibrous membrane structures exposed to well-defined local loading conditions.

By collecting qualitative and quantitative data from live silkworms spinning on top of pre-fabricated flat patches a correlation between the nature of material distribution and the geometrical characteristics of the patch was successfully predicted. These results, combined with future research currently under way, have significant implications for structural analysis protocols of fiber-based systems. Additionally this work may also carry implications for biologically-inspired digital design and fabrication. Here, the relationship between the global, top-down design of a constricting
“environment” designed artificially by the designer informs its local, bottom-up material manifestation as portrayed by the biological organism (the silkworm). Finally, the *Bombyx mori* silkworm may be considered as an autonomous agent in processes of design optimization. As this research has shown, this project opens up new possibilities for the use of biological processes as forms of computation.
Chapter 3

Compact & Tunable Material Deposition in Digital Fabrication

3.1 Introduction

Based on the insight gained in Chapter 2 of this thesis, this chapter presents an array of extrusion heads that aim at increasing material tunability and portability. The figure below illustrates the collections of heads I designed, developed, implemented and tested in the context of specific design projects and their design constraints.

Figure 3-1: Six extrusion heads for tunable material deposition were designed as part of this thesis. Amongst those tools is a freeform extrusion head for tunable geometry without the need for auxiliary support structure; a fast thread deposition head and a fiber winding head for tunable compressive and tensile strength respectively; a portable cable suspended paste droplet extrusion head for tunable drop size of paste material; and a chitosan gel extrusion head for tunable plasticity.
3.2 Compact Freeform Extruder Head for Tunable Geometry

Figure 3-2: Highlighted: a freeform extrusion head for tunable geometry without the need for auxiliary support structure.

3.2.1 Introduction

Biological Systems

Material systems in Nature are typically composed of graded composites grown and adapted from a single material system rather than an assembly of parts [Oxman, 2011]. More so, growth in the plant and animal kingdoms rarely follows rectilinear paths confined to single planes, but instead spreads through space in response to various factors and stimuli [Braam, 2005]. Identical systems and matching fabrication processes can result in substantially different structures, depending on external environmental constraints. Such is the case with Cecropia silkworms, which can produce silk cylinders and sheets in addition to the canonical silk cocoon [Kloot and Williams, 1953].

In Nature, form typically follows function such that the composition and properties of a material system vary locally as part of the fabrication process. *Bombyx mori* silkworms vary the porosity and amount of sericin—a bonding agent between fibers found throughout the layers of their cocoons producing a highly bonded network in inner layers compared with outer layers [Chen et al., 2012]. Orb-weaving *Araneus diadematus* spiders spin a wide variety of different silks, ranging from the incredibly stiff and strong dragline-silk to the glue-coated and highly extensible viscid silks [Guerette et al., 1996].
In all of Nature’s systems, the optimization of material usage and hence metabolic cost plays a necessary role. In tensile systems such as spider webs, there is little material waste as structural support is an integral part of the web design [Gosline et al., 1986].

3.2.2 Background

Additive manufacturing technologies emerged in the 1980s as a promising method for fabrication and construction automation [Jacobs, 1992]. Today, these additive fabrication technologies operate across a wide variety of materials and are used in applications ranging from medical implants to large-scale prototyping. Fused deposition modeling (FDM) systems in particular are found in both hobbyist and professional 3d printing platforms such as the MakerBot Stepstruder, and more professional grade systems such as the Stratasys Dimension 3D printer. Consistent to all of these systems is the need to use support materials to fabricate certain thin-walled or particularly complex geometries [Levy et al., 2003].

3.2.3 Goals and Objectives

Interest in Freeform Printing was inspired by the concept of self-supporting fiber-based construction in contrast to the scaffold-based robotic weaving and wrapping explored previously [Tsai et al., 2010]. Here, various natural examples were examined, including silk producing bi-valves, spiders, and silkworms, both wild and domesticated (Fig. 3-3). One of the guiding principles observed among the different natural systems was the concept of producing a continuous fiber-based construction method. (Fig. 3-3).
Figure 3-3: (L.) *Bombyx mori* silkworm cocoon sequence. (R.) *B. mori* silkworm spinning in half-sphere.

Initial extrusion of a mono-material was pursued through the employment of a 6-axis KUKA KR5 sixx R850 robotic arm as a means to increase the scale capacity (build volume) of the final result (Fig. 3-4). The ability to create knitted or woven structures requires high levels of robotic dexterity or multiple agents, otherwise resulting in the process being rate limited by fiber component length and splicing or tangling of the material.
3.2.4 Methodology

Initial Exploration

Preliminary tests explored the use of a Stepstruder tool-head with MakerBot Acrylonitrile Butadiene Styrene (ABS) filaments to test the concept of drawing a fluid plastic material through space (Fig. 3-5). As a departure from small-scale ABS tests, a custom extrusion tool for attachment to a robotic arm was developed. The design of the tool was based on research into current extrusion devices in industrial applications. The core of the tool is a large 20.6 mm diameter auger-type masonry drill bit cut to a length of 184.5 mm. The goal was to make the housing as compact as possible in order to achieve a high degree of control over the maneuverability of the tool in the robot workspace. (Fig. 3-5).
Tool Development

A 3d model of the tool was developed in Rhinoceros 5 for design development, visualization and fabrication (Fig. 3-6). The housing for the extrusion chamber was constructed out of 50 mm diameter aluminum round stock.

Figure 3-5: (L.) ABS Filament freeform extrusion. (R.) Custom HDPE extruder mounted on KUKA.

Figure 3-6: (L.) Digital model of extrusion tool (R.) Extrusion tool with variable tip.
The body and other cylindrical parts of the extruder were turned from round stock on a CNC lathe. The housing was bored to accept the auger bit and then machined from the other end to allow the extruder to accept various interchangeable extrusion tips via three setscrews. The output end of the tool also retained a substantial wall thickness between the bore and the exterior to allow for the placement of up to twelve cartridge-heating elements. Near the top of the tool, the auger bit was machined with an indexed shank to accept a series of water-jet-cut aluminum spur gears. Near the top of the housing at the furthest point from the heater elements an opening was created to feed plastic pellets. Aluminum motor mounts were created using a flexural design to carry the NEMA 23 stepper motor. The motor is controlled by a Gecko G201X Digital step driver to drive the gears turning the auger bit. When the auger bit is turned by the gears, a steady supply of plastic pellets is fed from a hopper through flexible tubing via a venturi for material advancement (Fig. 3-6). As the pellets are transferred down through the housing, the heater cartridges heat the pellets to about 130 degrees C as regulated by an Arduino-controlled thermistor, while the downward pressure advances the molten material out through the selected tip.

**Material Tests**

For the proof-of-principle experiments, we chose high-density Polyethylene (HDPE), commonly used today for a variety of applications, ranging from storage containers and furniture products to professional lenses and pipes. In contrast to low-density Polyethylene (LDPE), the HDPE polymer backbone has no branches, yielding stronger intermolecular forces and denser packing. It is therefore more crystalline and exhibits a higher ratio of tensile strength to density – a property crucial to its ability to support itself during printing. In addition, its relatively low melting temperature of 130 degrees C allowed us to melt, extrude, and harden it in the air using a compact setup that is easily mountable on the robotic arm.
Tip Development

A variety of tips were explored and developed based on material properties and deposition processing constraints. The initial tip was developed as a variable diameter and cross section tip (Fig. 3-7). With an additional stepper motor mounted near the bottom of the extruder, this tip is able to vary between a 10 mm round extrusion to an 8 mm triangulated extrusion profile. Following initial experiments with the variable tip (Fig. 3-7), a series of interchangeable tips were developed, including two tapered single diameter extrusion tips of different length. The diameter of these single extrusion tips consisted of a 3 mm extrusion hole resulting in a 4.5 mm final extrusion.

Additional tips were developed to enable more complex extrusion profiles. For example, one of the tips was designed with a flat ‘ribbon-type’ extrusion cross-section. The extrusion clearance measurements were 3 mm by 16 mm and resulted in a ribbon extrusion of 4.5 mm by 16.25 mm. Another tip enabled the generation of a hollow
tube-like extrusion with a series of internal fins allowing the molten plastic to flow around and reconnect between the interior walls of the tip and a cylinder shaped interior wall. Advanced versions of this tip incorporated a multi-strand approach inspired by the multi-parts or materials of silkworm’s “extrusions”. Two multi-strand tips were developed, one with a variety of self-similar holes and another with varying holes. The holes of the second tip contained larger diameter strands on the interior, retaining heat for reconnection; and thinner strands to cool more quickly to support the printing in 3D space (Fig.3-8).

Figure 3-8: (L.) Multi-strand HDPE extrusion close up. (R.) Multi-strand HDPE extrusion in space.
3.2.5 Results and Discussion

Testing

The initial variable extrusion was found to be promising in modulating the extrusion profile from a complete round strand to a triangulated tapered design. The single strand extrusion profile proved to be the best balance of both heat and rapid cooling for initial print in-space experiments. The first of the multi-strand extrusion experiments proved to be a success and allowed for a quicker vertical extrusion test with the fibers cooling in air. The multiple-strands have the potential for multiple-strand bundling as a way of providing additional support (as the structure progresses in vertical space) and self-alignment due to the forces of gravity.

The final multi-strand printing nozzle was modified for the original design to be both longer and thinner for increased agility when printing more complex structures. One of the challenges in many of the freeform printing tests was to provide for
material connectivity to plastic parts previously cooled and hardened. The revised multi-strand tip utilizes five thicker diameter holes at the center and along the outer perimeter, allowing for a balance between quickly cooling strands for structural support as the path is extruded and thicker slower cooling strands, which retain more heat and allow for better reconnection to existing cooled extrusions (Fig.3-9).

It was also found upon attempting more complex path planning and part printing exercises that a longer extrusion tip length allowed for much greater flexibility in the maneuverability of the extruder while attached to the six-axis robotic arm (Fig.3-9).

**Future Development**

While initial tests were highly dependent on developing custom tooling, future work may explore the further development of active heating and cooling at the tooltip, allowing for greater freedom of possible print geometries. Larger printed systems may be explored through leveraging the strand-like nature of larger printed cells that utilize fibrous interfaces at their edges to assemble a larger fibrous aggregate system.

Future tests could also benefit from substantially expanding the working envelope of the machine. This could, for instance, be a larger scale industrial robotic arm or an autonomous robotic system capable of transporting deposition material to the final desired location(s).

3.2.6 **Conclusion**

As of yet additive manufacturing methods typically rely on the use of support materials in the fabrication of certain geometries. These materials are used to support overhanging features and undercuts during the construction process, and are typically removed or dissolved upon completion of the print. In powder-based selective laser sintering (SLS) processes the excess material acts as the support of the printed structure, whereas thermoplastic deposition and resin curing processes require additional support structures that are themselves printed.

The research and experiments presented in this section focus on the intersection of biologically inspired design, fibrous construction, mono-material construction and the development of free-form printing. Applications for this novel process are varied
and range from product fabrication to furniture and architectural scale construction. With the elimination of support material in the printing process, printing speeds are increased, and waste is eliminated. The experiments presented in this section provide proof-of-concept for Freeform Printing without support materials. They represent a sustainable approach to additive manufacturing and digital fabrication at large, and point towards new possible directions in sustainable manufacturing.

3.3 Compact Fiber-pulling Head & Fast-thread Deposition Head for Tunable Fibrous Compressive Strength

Figure 3-10: Highlighted: a fiber winding head and a fast thread deposition head for tunable compressive and tensile strength respectively.

3.3.1 Introduction

Background
Additive manufacturing and digital fabrication processes such as 3D-Printing typically involve the layered deposition of materials with constant and homogeneous physical properties[1]. Yet all natural materials and biological systems are made of fibrous structures that are locally aligned and spatially organized to optimize structural and environmental performance[2]. Furthermore, construction processes found in the animal kingdom such as woven spider nets or aggregate bird’s nests are characterized by the animal’s ability to gen-
erate, distribute, orient, dandify and assemble fiber-based materials[Benyus, 2009, Hansell, 2005]. As a result biological structures (including animal architectures) are considered highly sustainable natural constructions[Benyus, 2009, Robbins, 2002, Hansell, 2005]. Many of these constructions are “designed” by insects well known for their ability to construct highly sustainable structures made of fiber composite materials such as silk[Sutherland et al., 2009].

The section reviews a suit of analytical protocols designed to examine the process of constructing a silk-cocoon by the silkworm. Following, I demonstrate a set of design tools created to reconstruct the cocoon in various length-scales using a 6-axes KUKA robotic arm.

**Problem Definition**

Fiber-based 3D constructions with spatially varying composition, microstructure and fiber-orientation are omnipresent in Nature[Seidel et al., 2008]. In contrast to natural materials and biological structures, industrially fabricated constructions, such as concrete pillars and façade panels are typically volumetrically homogenous[Oxman, 2011]. Additive manufacturing platforms such as 3-D printing, provide for the generation of highly complex geometrical forms. However, despite their formal complexity, these products and building components are still typically manufactured from materials with homogeneous properties. Compared with biologically constructed fiber-based materials, homogenous constructions fabricated using additive manufacturing technologies are much less sustainable: from a material perspective - homogeneous materials offer less potential for structural optimization; and from a fabrication perspective - additive manufactured components are constructed in layers, relying on the deposition of significant amounts of wasted support material[Oxman et al., 2012c].

### 3.3.2 Fiber-Based Construction in Nature

**Introducing the Silkworm Bombyx mori**

Silk is one of the most ancient, expensive, and highly valued materials in the world[Omenetto and Kaplan, 2010]. It has many applications in textiles, medicine, and industry[Frings, 1987]. This silk is most commonly produced by the domesti-
cated silkworm *Bombyx mori*. It constructs its cocoon using composite fibrous material made of fiber (fibroin) and binder (sericin) in order to provide shelter during its transitional stage of pupation[Zhao et al., 2005, Rockwood et al., 2011]. A single fiber is used to construct the cocoon, which is approximately one kilometer in length. The silkworm starts by spinning a scaffolding structure in any three-dimensional space, given it can triangulate and attach its fibers parasitically to its immediate environment. While spinning this scaffolding it will close in onto itself to begin to construct its cocoon within the scaffolding structure. The cocoon itself can be characterized by changes in fiber quality transitioning from the inner layers to the outer ones[Zhao et al., 2005].

**Silkworm Motion Tracking**

Various methods for motion tracking data were considered. Popular methods include visual routines using cameras and/or sensor-based systems[Black and Yacoob, 1995]. The fact that the silkworm cocoons itself within its structure eliminated the use of video-based techniques unable to capture construction processes internal to the cocoon. The challenge was to create a motion-tracking rig on a very small scale that could capture motion data of the silkworm from inside the cocoon as well.
Figure 3-11: Motion tracking of the silkworm *Bombyx mori* using magnetometer sensors and a 1mm x 2 mm magnet.

An experimental sensor rig 40 mm x 40 mm x 40 mm in dimension was developed using magnetometer sensors placed on 3 planes of the cube. This allowed for data capturing from a 1mm x 2 mm magnet attached to the silkworms’ head with cyanoacrylate (Fig. 3-11). After attaching the magnet to the silkworms head, the silkworm was placed within the described space. As expected the silkworm attached its fiber scaffold-ing structure to the walls of the described rig and constructed its cocoon within this defined space.
From the collected data set of Cartesian x, y and z points, a point cloud was visualized (Generative Components Software) as a path, sequenced in time as seen in Figure 3-12.
Motion Tracking Data Evaluation and Speculation for
Robotic Emulation on Larger Scale

The captured data demonstrates a clear overall cocoon shape constructed from over 1,000,000 points. The detailed motion path is slightly disrupted by the polar positioning of the magnet as the silkworm spins its cocoon.

This experiment establishes the possibility to convert biological data into robotic motion. The silkworms' actual motion path can be translated into a readable language (Cartesian x,y,z points) and passed on to a robotic arm or any multi-axis material deposition system. This in turn can inform the robotic arm movement in terms of distribution of fiber structures as well as precise fiber placement, as this work-in-progress path simulation demonstrates.
**SEM Imaging across Multiple Scales**

In order to investigate local fiber placement of the cocoon as well as to gain a better understanding of the scaffolding structure, SEM images were taken of the outer layer of the cocoon.

Figure 3-13: SEM images of the silkworm *Bombyx mori* cocoon across multiple scales (Photo credit: James Weaver, 2013).
Figure 3-13 shows the overall all cocoon form. Its shape and curvature radii largely depend on the silkworm's own body structure (i.e. its bending radii) as well as its overall length. This could also inform robotic principles in terms of using the robotic arms reach envelope as a limiting factor or constraint. Furthermore, fiber self-alignment shown in figure 3-14 constitutes a significant aspect of fiber-based construction, as the stresses seem to be locally equalized across varying fiber distribution on global scale. This aspect is further discussed in section 3 below.

3.3.3 Fiber-Based Digital Fabrication

*Strategies for Robotic Fiber-based Construction on Larger Scales*

Based on the analytical protocols developed and reviewed above, a synthetic approach for translating the biological process into a digital fabrication protocol was developed. Several synthesis methods were developed each mimicking a distinct aspect of the silkworms fiber placement process and its material organization strategies across scales. Three robotic-end-arm-tools were developed to test and analyze novel avenues for fiber-based robotic construction inspired by the silkworms construction methods.

The first approach explores 3D digital construction using a single fiber or a combination of several composite fibers forming a single structural element. A thermoplastic extruder was developed in order to accomplish fiber or multi-strand continuity.

The second approach explores the dual stages in the silkworms cocoon construction process: (a) parasitic construction and (b) cocoon spinning.

*Synthesis 1: Multiple Strand Thermoplastic Extrusion*

A Free-Form-Printing tool - inspired by concepts of fiber self-alignment - was developed and built. A specially designed nozzle for a custom-built high-density-polyethylene (HDPE) thermoplastic extruder was built to allow for local self-alignment of individual strands (Figure 3-14). Self-alignment of fibroin and sericin as observed in the silk fiber inspired the design of an extruder nozzle, which combines fiber and binder as a single material system.

The extruder nozzle contains multiple outlets laid out in a circular configuration.
around a single central and larger opening. In this way the HDPE polymer can flow through, before being rapidly solidified by active air-cooling. In this method, the central strand is stabilized by the surrounding thinner strands as well as the outer strands reconnecting to previously extruded strands in close proximity to the overall structure [Rauwendaal, 2001]. Figure 3-14 compares between the biological extrusion process using silk and its digital-fabrication counterpart using composite HDPE. Based on the mono-material synthesis approach using thermoplastic, further experimental synthesis approaches were developed and simulated.

**Synthesis 2: Fiber Placement Tools**

In this approach, the silkworm cocoon construction is divided into two stages: the first being the parasitic scaffolding and the other being the cocoon construction process itself, as the enclosure within the scaffolding. Fiber-placement in these two phases of the silkworm cocoon construction differs greatly in material quality, organization and function. As the silkworm constructs the scaffolding it "parasites" to its environment, attaching its fibers and pulling it across, connecting to another part of the space repeatedly, building up a three-dimensional web. In the second stage it builds its cocoon in a figure-8 pattern, building up wall thickness for the cocoon over time by constantly reconnecting the fibers locally inside the previously built scaffolding.
Figure 3-14: SEM image of silk fibers (top left), HDPE extrusion (top right), and thermoplastic extruder on KUKA robotic arm (bottom).
**Synthesis 3: Parasitical Attachment and Fiber Pulling**

Two robotic end arm tools were developed. The first pulls a continuous 2 mm polypropylene fiber through epoxy resin and is used in combination with a robotic rig describing the reach envelope of the robotic arm. This ‘scaffolding tool’ is designed to attach the resin-soaked fiber from point to point on the provided external rig. This system relies on a modular hook system on which the robotic arm can attach the fiber ‘parasitically’ to the hooks.

As seen in Figure 3-15 the scaffolding of the silkworm *Bombyx mori* consists of a loose-networked structure, which relies on an external three-dimensional space to which it attaches itself to. Finally, a rig was developed onto which the robot can attach fiber whilst pulling the fiber through a resin bath right at the tool head, not unlike the biological process.

**Synthesis 4: Fast Deposition Tool**

A secondary end-arm tooling was developed, which is a combination of depositing fiber in controlled speeds while spraying binder onto the fiber. This method also requires a robotic rig and is used in accordance with a previously made scaffolding structure to adhere to, which is described above. The scaffolding structure would act as a mold for the ‘cocoon’ shell to be placed upon, and can vary in density according to previously mentioned distribution maps acquired through motion tracking. This tool places a fiber on top of this scaffolding structure by pushing 1 mm polypropylene string by means of two motorized rollers (Figure 3-16) whilst spraying them with contact adhesive. The speed of the deposition and the robotic movement must be synced in order to achieve varying densities. These fibers build up a layer of fiber at a loose configuration based on the 8-figure patterns. Depending on the robotic movement and speed, varying densities and gradients can be achieved.
Figure 3-15: Fiber pulling tool (top), fiber pulling tool on KUKA robotic arm with external hook structure (middle), comparison of epoxy resin-soaked polypropylene twine (bottom right) and SEM image of scaffolding silk fiber (bottom left).
The experiments demonstrate that an external structure (equipped here with hooks) is required in order for the robotic tool to “print” with fibers. These works-in-progress demonstrate that it is possible to create fiber-based rigid structures, which may be used in the manufacturing of products such as lightweight furniture and building components. The secondary process of fast fiber deposition demonstrates the possibilities for creating additional structural integrity in a component as well as varying properties across its inner wall. The combination of these two processes could lead to a novel and customizable robotic construction process for large-scale fiber-based composite parts.
Figure 3-16: Fast deposition tool on KUKA robotic arm, SEM Image of outer silk-worm cocoon surface, composite material from polypropylene twine and contact adhesive.
3.3.4 Digital Fabrication of Fiber-Based Constructions as a Case for Sustainable Manufacturing Results, Conclusions and Outlook

The research demonstrates the need for sophisticated analytical tools in translational research of fiber-based systems across scales. Such analytical protocols are required for the synthesis of robotic fabrication processes via the development of robotic-end-arm tooling to facilitate experiments in the field of sustainable digital fabrication. Two synthetic approaches in digital fabrication were presented using three distinctive custom end arm tools.

Further research into the topic will include the combination of the described robotic-end-arm-tools with motion tracking data, enabling direct comparisons between micro scale structures and their robotic macro-scale counterparts. The process of data collected from the biological world combined with experiments into novel fiber placement methods will lead to integrative and sustainable fiber-based manufacturing using Nature as inspiration and technological advances as facilitators.

3.4 Compact CNC Fiber Placement Head for Tunable Tensile Strength

Figure 3-17: Highlighted: a fiber winding head for tunable tensile strength.
3.4.1 Background and Motivation

**Fiber-based Construction**

Digital fabrication processes such as layered manufacturing typically involve the layered deposition of materials with constant and homogeneous physical properties [Tao et al., 2012]. Yet most natural and biological materials are made of fibrous structures locally aligned and spatially organized to optimize structural and environmental performance [Benyus, 2009, Omenetto and Kaplan, 2010, Oxman et al., 2012a, Oxman et al., 2012b].

Within the fields of product and architectural design – specifically the automotive and avionic industries – fiber-based digital fabrication has typically been confined to the development and application of high-performance composites [Beesley et al., 2011]. These materials and their related processes are typically toxic and harmful to the environment. Based on previous research and inspired by the *Bombyx mori* silkworm, this research explores the possibility of merging digital and biological fabrication to deliver a holistic and sustainable design approach in the production of non-woven fiber-based constructions [Oxman et al., 2012a].

Construction processes found in Nature such as woven spider nets or aggregate bird’s nests are characterized by the animal’s ability to generate, distribute, orient, densify and assemble fiber-based composite materials. [von Frisch and von Frisch, 1974]. Spiders for example can generate fibers with varying properties based on a particular need or function. These fibers are optimized for a wide range of different conditions including, but not limited to, mechanical properties such as strength and toughness. In addition to many existing types of silks, the silk itself may be rapidly adapted to different parameters during the silk spinning process. The final webs take into account a delicate balance of function, environmental conditions and material efficiency as limited by the energy resources of the spider [von Frisch and von Frisch, 1974, Vollrath, 2000]. Similarly the silkworm can control the ratios of fibers and matrix to generate a wide array of mechanical properties ranging across tensile and compressive structures [von Frisch and von Frisch, 1974, Omenetto and Kaplan, 2010].
3.4.2 Basic Research into Fiber-based Cocoon Construction of Silkworms

*Anatomy, Behaviors & Methods*

The *Bombyx mori* silkworm is an arthropod with a body of approximately two to three inches in length. A break in the legs around the mid portion of the body allows the worm to bend freely from side to side in its typical figure-eight motion (Fig.3-18). The silkworms spinneret is located near its head allowing the organism to extrude upwards of one-kilometer raw silk fiber. It traditionally spins silk in its fifth instar after one to two months of feeding on mulberry leaves as it matures into a silk-producing caterpillar. When prepared to spin, the silkworm typically triangulates a three-dimensional space or corner forming a tensile structure within which forms the cocoon [von Frisch and von Frisch, 1974].

![Bombyx mori silkworms deposits silk fiber on a digitally-fabricated scaffolding structure.](image-url)

Figure 3-18: *Bombyx mori* silkworms deposits silk fiber on a digitally-fabricated scaffolding structure.
Silk production typically involves the harvesting and soaking of completed cocoons in a soapy water bath. The edge of an individual fiber is then pulled out of the bath and spun onto a spool for silk thread production. This production method requires the spinning of a full cocoon and a shortened life cycle for the silkworm, eliminating the opportunity for reproduction.

**Advanced imaging techniques and quantitative analysis of silk cocoons**

Basic research was conducted to further observe, understand and predict the motion and material deposition behavior of the silkworm implementing the following tools, techniques and technologies:

(1) Dynamic tracking was achieved by the application of magnetometer motion sensing to motion-capture a silkworm over the course of a 3 day cocoon construction period during which time the silkworm was tracked by attaching a miniature magnet to its head. The organism was placed within a boxed space fitted with three magnetometers capturing the worms movement in 3-D space. Data collected was converted into a visual representation of a point cloud (Fig. 3-19).

![Figure 3-19: (L to R) A *Bombyx mori* silkworm in magnetometer testing rig. Resulting magnetometer testing rig data point visualization.](image)

(2) Wide-angle high resolution MicroCT and SEM imaging techniques were developed and implemented to analyze the organizational properties of silk textures across various length-scales and species (Fig. 3-20). SEM imaging techniques enabled micro...
scale analysis of material property variation across the transversal and longitudinal sections of the cocoon.

Figure 3-20: Biological analysis (L to R): 2300x mag. polychromatic micrograph of the silk support scaffold of a *Bombyx mori* cocoon; 25x mag. overview micrograph of a *Bombyx mori* cocoon; 300x mag. polychromatic micrograph of the external surface of a *Bombyx mori* cocoon color coded to reflect surface typography; 40x mag. isometric view micrograph of an equatorially bisected *Bombyx mori* cocoon; 2500x mag. Polychromatic micrograph of the external surface of a *Bombyx mori* cocoon; 230x mag. plan view micrograph of an equatorially bisected *Bombyx mori* cocoon. Scanning electron micrographs in collaboration with James Weaver, Wyss Institute, Harvard University.

(3) Templated fiber-spinning experiments: it was observed that when spinning on a relatively flat environment the silkworm will generate a flat non-woven silk patch. Building on this observation, coupled with previous research,[Lawrence et al., 2008, Omenetto and Kaplan, 2010, Tao et al., 2012] a suite of environments with varying
morphological features was developed in order to explore the relation between surface features and fiber organization (Fig. 3-21) [Oxman et al., 2012a, Oxman et al., 2012b].

Figure 3-21: Top and elevation views of the Maltese Cross study series where surface morphologies vary in sectional height from 0 (flat) to 25mm. Flat patches are spun onto morphological patches less than 20mm in sectional height beyond which the full 3D silkworm cocoon appears. Variations in designed surface morphology yield corresponding variations in fiber density, property and overall organization.

Experimental results determined the following: (1) a 3D cocoon structure emerged only at a sectional height of 21mm height, below which a tent-like structure in the form of a rectangular pyramid was spun. In the absence of this height, a non-enclosed surface patch was spun; (2) fiber density typically varied as a function of the distance from the central vertical pole to surface boundary. This may point to a local optima condition requiring the least amount of energy for the construction of a strong stable structure within a given timeframe; (3) boundary contours were typically denser.
assume this is due to the silkworm’s constant search for a vertical pole tall enough to allow for cocoon construction.

### 3.4.3 Scaling: Computation and Digital Fabrication

**Pavilion Computation**

The pavilion was designed and constructed in two phases: the first phase consisted of digitally fabricating a scaffolding envelope made of silk fibers and the second phase consisted of deploying a swarm of silkworms that spin a secondary silk envelope. A set of apertures built into the initial envelope capture light and heat thus controlling the distribution of silkworms on the structure.

Overcoming current limitations of existing computer aided design (CAD) tools; a parametric environment was developed that facilitates the design and fabrication phases of the project enabling continuous iteration between digital form finding and physical fabrication processes. As such this computational tool also served to mediate between environmental input, material properties and organization as well as biological fabrication constraints. In addition, the tool enabled real-time evaluation of multiple design solutions.

Our main goal was to develop a holistic computational design environment able to simultaneously capture and process multiple sets of complex constraints in real-time. Most of these constraints are difficult or impossible to capture using current CAD tools. Amongst them is the ability to automatically determine for every digitally woven silk fiber what is the conformal distance or space within which the silkworm can spin, enabling the convergence between the digitally laid fibers and the biologically spun filaments.

A subsequent goal was to computationally embody the geometrical complexity and scalability of the Pavilion, as well as the scaffolding resolution and the range of fabrication tools implemented. The tool developed informs the designer about overall material organization as well as the effects of the biological parameters (such as silkworm motion range) on the final design.

The generative environment includes a new library designed on top of the RhinoCom-
mon build that runs on the Grasshopper plug-in (within McNeel Rhinoceros 3d Mod-
eler). The library is comprised of a set of routines that enable the shaping of a
lightweight fibrous environment. The following data sets informed the algorithm for
scaffolding thread geometry: the first set is comprised of the fabrication constraints
captured by the algorithm. These constraints are informed by the robotic manufactur-
ing platform, along with its prescribed gantry size and tool reach. This set generated
the need for the spherical structure of the pavilion to be subdivided into a set of sub-
structural patches. The patches conformed a truncated icosahedron whose faces fit
the robotic manufacturing bed. The second set of constraints originated in two data
maps; the first encoded the specific on-site solar trajectory and the second provided
an opening radius multiplier to generate organizational fiber variation. Combined,
these two maps informed the position and size of the pavilion apertures (Fig.3-22).
The third set of constraints is linked to the silkworm's biological characteristics, with
the goal of providing maximum silk deposit reach.

Figure 3-22: Computational projection paneled dome solar mapping. Computational
projection paneled dome aperture distribution mapping. Computational protocols
developed by Jorge Duro-Royo.
For each aperture – the position and size of which is informed by the site's light conditions - the computational protocol identifies a continuous tangent circle on the spherical geometry (Fig.3-23). Subsequently, it is then converted into tangent line segments represented in 2D matching the patch fabrication representation. For each such circle a parameter controlling the resolution of the tangents was assigned relative to its geometry. This parameter determines the ratio between local fiber gradients to overall fiber distribution and organization. The algorithm then checks for each aperture if it is contained within a prescribed patch, multiple patches or none, and classifies this information as data lists. For each patch containing a full or partial aperture, the algorithm computes the following: (1) aperture formation in relation to the overall image of a continuous thread (Fig.3-23). (2) Thread redistribution across apertures providing balance between aperture distribution and continued thread allocation across the surface area of the overall volume (Fig.3-23). (3) Contour attachments for local continuous threads (Fig.3-24). (4) Scaffolding thread spacing conformation to biological parameters of the silkworm weaving pattern (Fig.3-25). (5) Robotic tool path its fabrication (Fig.3-25).

Figure 3-23: Computational single aperture generation logic. Final computational global aperture generation distribution. Computational protocols developed by Jorge Duro-Royo.
Figure 3-24: Computational silkworm spinning range calculation. Computational unfolded panel and tool path diagram. Computational protocols developed by Jorge Duro-Royo.

A final overall visualization of the pavilion, aluminum frame profiles for water jet manufacturing of the patches (visualized as the polygonal line segments), and unfolded of tool paths for CNC weaving are then generated as output (Fig.3-25).

Figure 3-25: Computational unfolded panel detail. Computational unfolded overall panel layout for fabrication. Computational protocols developed by Jorge Duro-Royo.
Silk Pavilion Digital Fabrication

Based on the analytical protocols developed and reviewed above a digital fabrication approach was developed that supported our findings with regards to the worm's possible range of motion and deposition behavior enabling the merging between digital fabrication tools and biological construction.

Initial tool path development was tested with a three-axis CNC (Computer Numerically Controlled) machine. Initial computational paths were explored and implemented as traditional milling tool-paths without using the machines spindle activation. These tests were originally developed as a drawing method prior to the development of the thread deposition tool (fig. 3-26).

![Spring steel CNC threading tool and silk thread.](image)

Figure 3-26: Spring steel CNC threading tool and silk thread.

Continued development of the CNC tool path output (from the digital model to the machine) enabled the development of a basic tool that allowed for the deposition of thread as a spool or roll based material. The gantry of the three-axis machine carried the rolls to be replaced as required based upon the panel to be fabricated.
A tool tip was developed that could be affixed into the normal collet design of the cutting head; the spindle would remain off and in a locked position. The spooled material could then be fed down through the tool tip inside a low friction HDPE tube. The tube ends in a custom made press fit bearing attached to a rotating shaft with a spring loaded foot where the string could exit smoothly and in accordance with the direction of machine travel. The deposition of a lightweight material onto a temporary aluminum frame allowed the machine to run at higher velocities than normal cutting operations aiding the speed of the fabrication process.

The perimeter of the unfolded 2D dimensional panels making up the overall form of the structure was designed as perimeter scaffolding structures. They were water jet cut from aluminum in order to maintain the deposited silk fibers during the fabrication process. The choice of a component-based assembly was dictated by the relatively large size of the overall structure and the limitations given by the gantry size of the CNC spinning tool. Designed as temporary support, these panels could be reassembled after weaving to maintain the overall geometry of the system while installing it into a tensioned state within the atrium space (Fig.3-27).
Figure 3-27: 3-axis CNC machine adapted as CNC deposition tool. Custom threading tool, temporary aluminum scaffolding and MDF jig.

The frames were developed with small hook elements to allow for the laying down of fiber. A release mechanism enabled the extraction of the frames once the panels were joined together and the structure was positioned in space. Between joining edges of each frame was a small rubber coated frame of piano wire to which the vertex nodes of the structure were affixed. The vertex nodes would be used in attaching the tensile structure to its surrounding environment and the piano wire was the medium around which the edge of each panel was affixed (Fig.3-28).
Figure 3-28: Knotting of vertex connections of non-woven silk patches on temporary aluminum scaffolding structure.

Once the truncated icosahedron panels were assembled and knotted edge to edge, the overall structure was raised to its proper height and location. Following, a series of tension lines were deployed. Each of the lines was affixed to a custom designed acrylic clip; each point location was calculated as part of the digital model of the vertex normals intersection within the space. Tension cable lengths were measured, located and labeled. Once the structure was in place, the entire vertex and centroid tension lines were installed and tensioned to their marked lengths suspending the metal frame and the structure in space. At this point the frames were removed starting from the top of the structure and working down in circular fashion. Following the removal of the frame some tension was lost that was recovered after the centroid suspension lines were tensioned. The bottom of the structure was affixed to a 25mm thick MDF floor structure with a white vinyl covering.
*Silk Pavilion Biological Fabrication*

Parallel to the digital fabrication of the primary structure 6,500 silkworms were raised through the remainder of their fifth instar, feeding on a diet of mulberry leaves prior to the silk spinning phase (Fig.3-29). Reared in a light, and temperature-controlled room at the MIT Media Lab, the silkworms were fed and monitored over the course of several weeks. As the worms began spinning they were transferred onto the tensioned silk structure with a protective fence and drop cloth in place.

![Image of silkworms](image)

Figure 3-29: Approximately 1000 *Bombyx mori* silkworms upon arrival in the 5th instar.

Over a ten-day period all silkworms were positioned on the scaffolding structure, typically initiating spinning from the bottom rim upwards (Fig.3-30).
Figure 3-30: View through pavilion apertures as the silkworms skin the structure.

Most silkworms were found to settle into a single space over the surface area of the structure spinning flat patches in circular motion. In addition, most silkworms were found to migrate to the highest surface patch of the structure possibly due to a combination of high temperature, low lighting conditions and decreased metabolic cost that is the result of horizontal movement (Fig.3-31).
Figure 3-31: Top view of the Silk Pavilion as approximately 1,500 silkworms construct the fibrous composite.

Following two to three days spinning the silkworms were released from the structure and collected on a drop cloth at the bottom of the dome. The silkworms were able to continue their cycle of metamorphosis into a silk-moth, including egg laying and reproduction.

3.4.4 Conclusion

Potential Applications

The Silk Pavilion explores the duality of digitally and biologically fabricated structures by proposing a templated construction approach to Fiber-based Digital Fabrication. In this approach digital tools are implemented to deliver a highly differentiated scaffold on top of which a biological system is deployed. The two systems are complimentary: while one provides for the load bearing paths of the structure the other strengthens these trajectories and acts as skin. Moreover, the biologically deposited
silk embodies qualities associated with its scale that could not have been achieved using current digital fabrication tools. The silkworm-spun nonwoven fibroin adheres to and wraps around the digitally deposited silk fibers and provides for a fibrous infill due to the interaction between the two chemical agents deposited by the silkworm: the fibroin that acts as fiber and the sericin that acts as glue or connective tissue. The templated construction approach can be implemented using other types of digital fabrication tools and biological systems. In this respect, the computational environment developed for this project can be considered a “generative” one: it can address other similar problems across a range of scales and across an array of fabrication methods, environments and biological systems of choice.

Several potential applications may be considered as potential outcomes of this research. With regards to the direct potential for biological fabrication combined with digital fabrication, I consider valuable experimental data affirming the relation between the scaffold surface morphology and the biological fiber organization (Fig.3-31). Further research will explore various techniques for templating biological fabrication in order to generate highly controlled and tunable functional gradients of material properties. New types of high-performance textile composites may be designed in this way, not unlike the composites observed on the pavilion which combine internal and external natural-silk wrapping of the synthetic threads. In addition, direct silk fiber deposition onto a scaffolding structure not only bypasses the processing of silk cocoons into thread and textiles, but also promotes a more sustainable silk harvesting cycle (Fig.3-32). Finally, with regards to decentralized swarm-like construction processes similar to the ones viewed in Nature, future development into the potential of collaborative construction behavior will be further explored.
Figure 3-32: Perspective view of the completed Silk Pavilion and the basic research exhibit focusing on fiber density distribution studies (far right).

3.5 Portable Paste-Drop Deposition Head for Tunable Compressive Strength

Figure 3-33: Highlighted: a portable cable suspended paste droplet extrusion head for tunable drop size of paste material.
The CableBot is a cable-suspended robotic 3D printing platform developed at the Mediated Matter group for which I contributed with the design and development of a portable drop paste extrusion head. The aim of the project was to achieve high levels of material tunability using a compact and portable single-node fabrication system, and high levels of communication using a multi-node fabrication system, respectively.
Figure 3-34: Time-based sequence of four cable suspended robot computational model. The overlapping build volumes provided the capability to build collaboratively. Computational protocols developed by Jorge Duro-Royo.

In this set up, cables from the robot are connected to stable high points, such as large trees or buildings (simulated as an array of mounting plates connected to existing structural beams within the installation space in the CableBot). This actuation
arrangement allows for moving large distances without the need for conventional linear guides. The system is relatively easy to set up for mobile installations, and afford sufficient printing resolution and build volume with spackle as the base material. Modifying two primary components in the motor pack assembly can scale up each individual system. By changing the dimension of a spool, which holds the SDPSi Syncromesh, timing cables control the length or reach of the machine. The relation of the size of the spool and length of the cable contained on it would then influence the constant force spring and the number of rotations that would be required to recoil the length of cable on the system.

Figure 3-35: Assembly of the stepper motor driven, constant force cable spools.

The development of a large but modular, compact yet adaptable material deposition system required precision control over the cable-based robot system that could carry any light material deposition tool at its apex. The low-tech material extrusions
system is much like the Skycam model, but rather than the attachment of a camera it features the attachment of a material deposition device.

Figure 3-36: One portable paste-drop deposition head suspended in the in-situ workspace. Material distribution is supplied from the top and a light acts as a beacon as the work envelope is a dimly lit space.

A material feed system was developed parallel to the development of the control system. Small-scale tests were carried out with baker bags using droplet deposition, which evolved into a pressurized material system from an empty adhesive canister pressurized with air, passing the spackle material through a tube to an extruder bud with a custom developed screw. A Gecko Nema 17 stepper turned the modified auger screw motor in pulse combinations of forward and reverse to control the droplet deposition.
3.6 Compact Chitosan Deposition Head for Tunable Plasticity

Figure 3-38: Highlighted: a chitosan gel extrusion head for tunable plasticity.
3.6.1 Introduction

The compact chitosan deposition head was designed to achieve highly tunable fibrous material deposition for deployment under the water. My tool was developed in the context of current group work for the construction of an underwater pavilion designed to immobilize clean seawater by deploying large-scale soft biodegradable chitosan gel structures that take on their morphology when submerged within the ocean's surface. The pavilion will be deployed in the vicinity of damaged reefs to enable coral spawning leading to reef regeneration. In time, the pavilion will be metabolized by fish and resurrected in the form of a growing reef.

Figure 3-39: Environmental Augmentation: Chitosan sample in water. Chitosan-based hydrogel binding is a biodegradable compound that can be further tuned to filter water by capturing suspended phosphorous, heavy minerals, and oil particles.
3.6.2 Material

Chitosan was selected as the base material for this project, due to its biodegradability and biocompatibility within ocean environments. In addition, chitosan combines the strength and toughness typically found in insect cuticles, crustacean, shells and other chitin-rich biological materials (Vincent, 2012, Ortiz, 2008). In order to deploy large quantities of chitosan under water, the properties of which can be tuned to achieve controlled plastic deformation, I developed a mechanized extrusion system that can contain, mix and extrude larger quantities of material.

![Figure 3-40: Introduction of fillers for tunability of geometric fluctuation between hydrated and dehydrated environments. Fillers left to right: Polyacrylamide, Sand & Polyacrylamide, Chopped Cellulose Fiber.](image)

3.6.3 Tool Development

The extrusion head was designed as a two-chamber head containing chitosan (semi-viscous material) while a second chamber would enable storage and dispensing of granular material based upon the filler requirements for tunable plastic properties. The semi-viscous material is contained in a large-capacity syringe and actuated via a stepper motor controlling the plunger, while the second chamber uses a syringe canister but for material holding. A stepper motor then turns a screw to advance the granular material to the tip. Further, a three-chamber system is currently under development that can house two chambers utilizing the stepper motor driven plunger actuation and an additional chamber to handle dry or granular dispensing. The nozzle
is designed as a 3-D printed tip to step the 8mm reservoir opening down to different diameters for extrusion testing.

Figure 3-41: Solid CAD model: Second design iteration utilizing 200mL syringes with non-captive shaft Nema 23 stepper motors to drive various material composites through interchangeable outlets.

The two rear mounted syringes utilized Nema Seventeen stepper motors with captive Acme Screws eleven inches in length. The motors were mounted to the frame and controlled via Sparkfun Motor drivers. The easy driver board is set up to run the two-stepper motors simultaneously thereby enabling variable extrusion rates and mixing ratios. A third Nema Seventeen stepper motor and a standard shaft were prototyped for granular dispensing. The easy driver was linked to an Arduino Mega and powered by an external bench power supply run at 12 V and 1.6 Amps in correspondence with the motor specifications. A simple forward and reverse stepper motor code was developed in C code in the Arduino IDE for testing of the motors.
3.6.4 Evaluation

Various machine paths were tested and evaluated for extrusion consistency and mechanical extrusion behavior including straight lines and cylindrical paths. Currently, robotic movement and extrusion are not explicitly linked. This allows for independent control of each motor-driven syringe and motion path velocity control. With the ability to vary each of these parameters individually in succession, there is more flexibility in the development of the tool as an experimental fabrication platform. Viscous and highly granular mixtures, such as soil and chitosan composite, proved to enable a wide range of formal plasticity.
Figure 3-43: Deposition head version 1 on Kuka robotic arm for the testing of x, y, z tool movements.
Figure 3-44: Sequence of deposition head version 2 on Kuka robotic arm for depositing tuned mixture of chitin filler, polyacrylamide and chitosan composite with 0.7mm nozzle for min. feature size.

Figure 3-45: Deposited tuned mixture of chitin filler, polyacrylamide and chitosan composite with 0.7mm nozzle for min. feature size.
Chapter 4

Conclusions

In addition to offering designs for customized extrusion heads for various purposes and material systems, the thesis also introduces an alternative to computer-aided manufacturing workflows. It does so with particular focus on portable heads or end-tools that can be implemented on different NC machines for material deposition in the context of the design of prototypes ranging from object to architecture scales.

Six unique design-fabrication tools were developed through the course of the thesis, which demonstrate rapid prototyping using customized tools for additive extrusion of tunable materials. With a focus on compactness and customization these designs can be utilized in the fab lab as unique or generic solutions for tunable extrusion. My hope is that these tools will prove to be valuable for future users and designers operating within a Fab Lab context, where digital tools are not segregated by length scale or disciplines and full access to production protocols is given where called for. It must also be noted that without this constant feedback from the in-lab development that we might have never arrived at a tool that actually incorporates biology into the process rather than only reproducing its behavior and thinking about biological based material systems. The following chapter discusses the workflow; its limitations, observation and results and makes recommendations for future work in this research area.
4.1 Designing Tools for Tools

At the heart of this thesis is the proposition that digital fabrication technologies that enable the deposition of multiple materials with variable properties on medium to large scales can promote the design and construction of novel properties and effective design and architectural systems. In order to realize this proposition in the context of full scale projects and prototypes, I have developed an array of deposition heads and other extrusion devices that enable tunable continuous material fabrication using a compact and customizable tool that can easily be attached to already existing robotic platforms and/or operate as a stand-alone DIY extrusion head. The tools I designed include a freeform extrusion head for tunable geometry with no support material; a fiber winding head and a fast thread deposition head for tunable compressive and tensile strength; a portable cable suspended paste droplet extrusion head for tunable drop size; and a chitosan gel extrusion head for tunable plasticity. See Figure 4-1 for a succinct summary.
Figure 4-1: Six extrusion heads for tunable material deposition were designed as part of this thesis. Amongst those tools is a freeform extrusion head for tunable geometry without the need for auxiliary support structure; a fast thread deposition head and a fiber winding head for tunable compressive and tensile strength respectively; a portable cable suspended paste droplet extrusion head for tunable drop size of paste material; and a chitosan gel extrusion head for tunable plasticity.
4.2 Tunability vs. Portability

Operating across the two trajectories of continuous material tunability and portability this thesis argues that highly portable, customizable, compact and tunable extrusion heads supporting multi-material printing and/or variable property printing can enable the digital fabrication of medium-large-scale sustainable products and architectural structures inspired by nature.
Figure 4-2: Six extrusion heads for material deposition located within the research framework matrix. Operating across the two trajectories of tunability and portability, this thesis argues that highly tunable, compact and portable extrusion heads supporting variable property printing of one or more materials can enable the digital fabrication of large-scale sustainable products and architectural structures inspired by the biological world.
4.3 Adding-On with Fab Labs: Pedagogical Significance

Inspired by Prof. Geshenfelds Fab Labs - low cost lab settings approximating high end fabrication labs from the microns and microsecond scale upwards [Gershenfeld, 2005, Gershenfeld, 2008, Gershenfeld, 2009]- the tools that I designed and developed range from portable tools developed for stationary platforms (such as the freeform FDM extrusion head) to completely independent tools that can be connected to each other to fabricate objects in a gantry-less setting (cable-bot paste droplet extrusion head). In addition to the range of portability, these tools can also be classified by their level of sophistication, from add-on tools to existing platforms to stand-alone portable extrusion heads. The former category appears to be promising for a new generation of digital designers and architects that can multi-material print using a robotic arm by simply adding on a pre-existing head to an existing robotic platform.

4.4 Method and Material Limitations

While this research attempts to challenge standardized or commercially available additive fabrication solutions it does not yet represent a truly digitally actuated tunable material system. Instead, I have realized 6 unique designs for extrusion heads that support continuous extrusion of tunable material properties in given scale targeting a specific material system.

Combined, the array of tools that I designed aims towards an enabling technology for a larger scale tunable material architectures. For example, the first tool developed aimed to explore feasibility of printing HDPE plastic in an FDM style without the use of a layer-by-layer approach and without using support material. While the tool was built, tested and several prototypes were made, I was able to quickly conclude that such a system might not be the best fit for a larger scale inhabitable environment due to the poor extrusion-to-extrusion adhesion between a crystallized and non-crystallized polymer extrusion. This type of work was however explored by
others around the same time such as Mx3D [Novikov et al., 2014] and the 3Doodler device [Flaherty, 2012] with success in different fabrication contexts.

This example, and similar other tools developed afterward, inspired the move towards fiber-based systems in closer reference to the silkworm as a biological model for digital fabrication. These tools, including the fiber pulling tool and the fast thread deposition tool, were also developed in a similar rapid prototyping fashion and tested for their results. The fiber pulling tool proved to be rate limited due to the number of successive layers of fiber that would be need to be placed to gain enough structural rigidity. In addition, the lack of compressive force applied to the composite before curing required the improvement of the layer-to-layer pressure of the wound fiber. The fast thread deposition tool followed a similar path: while not being rate limited by material feed, it would require a secondary system or scaffold to support the primarily tension based system.

The combination of quick turn development and testing of each of these respective designs allowed for the incorporation of the scaffold - a silk fiber placed scaffold - to become the substructure for our Silk Pavilion dome - a first large scale experiment of the sort. This project and the incorporation of 6,500 silkworms acting as "biological agents" challenged the design of the following tool: a system made of four heads working in parallel to deposit material drop by drop. We used low-cost paste materials to make inexpensive large-scale objects through a "collaborative" extrusion system. This project further suggested that the merging of custom tooling on existing robust platforms exhibited a better model for the faster development and testing of new additive approaches. The most recent and final example in the development of my six tools comes closest to a digital material system in the sense that is de-constructible. The hybrid approach of using an existing NC platform to develop a more customized tool for the deposition of Chitosan material was developed with input and guidance from the Wyss Institute [Fernandez and Ingber, 2012, Fernandez and Ingber, 2013, Fernandez and Ingber, 2014]. The aim was to deposit materials that can be mixed in an analog manner, but provide complete filler and binder separation when the printed objects are left for installation in an aqueous environment. This approach, though
not 3D printing in the traditional sense, allows for the printing of a biodegradable bio-based material in aqueous environments.
Bibliography


