Towards Swarm-based Design: Distributed and Materially-tunable Digital Fabrication across Scales

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Abstract

Towards Swarm-based Design: Distributed and Materially-tunable Digital Fabrication across Scales

By Markus Kayser

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, on December 8, 2017 in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Media, Arts and Sciences at the Massachusetts Institute of Technology

Throughout history, Nature has always been part of the discourse in Design theory and practice. The Digital Age in Design brings about new computational tools, redefining the role of Nature in Design. In this thesis, I aim to expand the role of Nature in Design and digital fabrication by investigating *distributed* fabrication strategies for the production of constructs that are, at once, large in scale and materially tunable—towards swarm-based design.

Digital fabrication approaches can be classified with respect to two basic attributes: (1) the degree of material tailorability, and (2) the level of collaboration between fabrication units. Conventional manufacturing is typically confined to only one of these attribute axes, with certain approaches utilizing complex tunable materials but virtually no collaboration, and others assembling pre-fabricated building blocks with high levels of intercommunication between fabrication units. A similar pattern is mirrored in biological systems: silkworms, for example, deposit a multifunctional tunable material with minimal communication between organisms; while ants, bees and termites operate as *multi-agent communicative entities* assembling larger constructs out of simple, unifunctional, 'generic' materials.

The purpose of this thesis is to depart from these uniaxial manufacturing approaches and develop a novel swarm-inspired *distributed digital fabrication method capable of producing tunable multifunctional materials* that is also collaborative. This research merges fiber-based digital fabrication and swarm-based logic to produce a system capable of digitally fabricating complex objects and large-scale architectural components through a novel multi-robotic fabrication paradigm.

I hypothesize that this design approach—its theoretical foundations, methodological set up and related tools and technologies—will ultimately enable the design of large-scale structures with high spatial resolution in manufacturing that, like biological swarms, can tune their material make-up relative to their environment *during* the process of construction.

Building on the insights derived from case study projects, fabricating with silkworms, ants, and bees, I demonstrate the design and deployment of a multi-robotic system erecting a 4.5-meter tall structure from fiber composites.

This thesis addresses the current limitations of digital fabrication, namely: (a) the material limitation, through automated digital fabrication of structural multi-functional materials; (b) the gantry limitation, through the construction of large components from a swarm of cooperative small-scale robots; and (c) the method limitation, through digital construction methods that are not limited to layered manufacturing, but also support free-form printing (*i.e.* 3D-printing without support materials), CNC woven constructions and digitally aggregated constructions.

Thesis Supervisor: Neri Oxman, Ph.D., Associate Professor of Media Arts and Sciences.

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The following served as a reader for this thesis:

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Acknowledgements

'Jack of all Trades and Master of None'

So what is a designer today—what am I after so many years of study and experiments? Arguably, a designer (who in former times might have been a craftsman or one part of the many parts of da Vinci) always had to adapt and invent new tools in order to produce and innovate on forms and functions of the built environment. However, in light of the craftsman having become (mostly) obsolete in the Industrial Revolution, and the disciplines having been divided into sub and sub-sub categories, design too often became a mere exercise in form, packaging products nicely. Design has come a long way from being an afterthought—'let's make it look good', spoken at the very end of innovation in technology and science. It's now fully integrated and even drives innovation again. The common saying 'Jack of all trades and master of none' describes what I consider the role of the designer today. Although laden with negative connotation, I think of it as a compliment, as the designer may act as glue or even as the facilitator of multidisciplinary work, taking part and being involved at the forefront of innovation, dabbling, tinkering and 'thinkering' in many areas, none of which he has formally studied. It is the symbiotic and collaborative research between the many fields of science and engineering, art and design that combine and at best unify to invent the future. And maybe, yes only maybe, the designer can become a master too, seeing the gaps and the overlaps, the in-betweens and the beyond in order to inspire and see what is important at this very moment in time and act on it. I believe that sometimes it takes a level of naivety to start a journey that may seem stupid and destined to fail, but I also believe that if such a journey is successful, its outcome will be all the more nuanced, lyrical and impactful.

The years I have spent at MIT, the Media Lab and in the Mediated Matter group have strengthened me in every way. I learned so much, I dreamed so much and I made so many things! I am so grateful to all of you, with whom I worked and from who I learned.

My first appreciation and gratitude goes to the Mediated Matter group and Professor Neri Oxman. Neri, you have been a mentor and friend. Your vision and tenacity to go beyond, and further still, impress me. But for me personally, your positivity has been an inspiration. I could come to you with any idea and you would always be open for a constructive discussion about the research with curiosity and positivity. Thank you!

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Erica Brookhyser, you were always there for us, keeping things running in your most amazing, practical yet gracious ways!

I thank my brothers, Simon, Niko and Raphael, for their unconditional support throughout my life and who I would always ask first before doing something stupid.

My parents: Thank you for giving me freedom and strength.

To my best friend Frederik, this is also yours and we will always be one.

Thank you Katha: I love you!

This is dedicated to my children Emil and Jakob, who give me the greatest joy imaginable!

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Chapter 1

Introduction:
Fabrication Technologies at the Interface of Nature & Design

1.1 Nature as Metaphor in *Traditional* Design & Fabrication

Throughout history, Nature has always been an integral part of design discourse, in theory and practice. However—at least from the Industrial Revolution to the early days of the Digital Age—designers have used Nature primarily as inspiration, implemented within a symbolic or an aesthetic language. From the famous Parisian Metro arches of the *Art Nouveau* era (Guimard 1900), through the teaching of the *BAUHAUS* in their study of Nature (Anker 2008), to more recent symbolic uses of embedded seeds in the *UK Shanghai Expo* pavilion by Thomas Heatherwick (Heatherwick 2010a), designers often treat Nature as metaphor in Design (Mateo and Ábalos 2007). It was Nature, which inspired the artists and designers of previous eras, and arguably still keeps us striving for equivalents in beauty and complexity in our manmade environments. While the modernists of the Bauhaus stripped products, paintings and architecture from any decorative elements resembling Nature, they embraced more abstract concepts inherent to and of Nature such as light, rhythm and patterns. For example, they took concepts taken into account when designing buildings with large glass windows, maximizing the experience of Nature by letting the outside in.(Itten 1975)

Figure 1.1: Entrance to the Abbesses Metro station (1900-4) by Hector Guimard, Montmatre, Paris Image by Steve Cadman, (Cadman 2007)

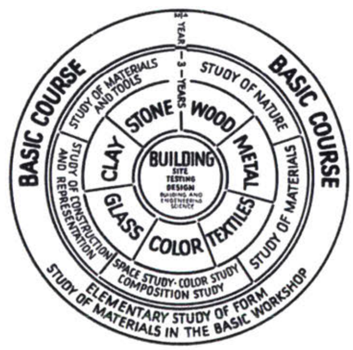

Figure 1.2: Bauhaus, Basic Course diagram. (Itten 1975)

1.2 Nature as Metaphor in *Digital* Design & Fabrication

The Digital Age in Design brings about new computational tools and algorithmic thinking, redefining the role of Nature in Design (Kolarevic 2001). The use of Computer-aided Design, Computer-aided Engineering and Computer-aided Manufacturing changes the way designers can analyze, emulate, express and utilize Nature's principles in Design to the point where they can digitally construct designs with much higher degrees of complexity (Oxman 2010). Yet, in large part, Nature is 'used' mainly as inspiration for form finding (Hensel, Menges, and Weinstock 2013).

Figure 1.3: Thomas Heatherwick's 'Seed Cathedral', Shanghai Expo Pavilion. (Heatherwick 2010b)

1.3 Expanding the role of Nature in Digital Design & Fabrication

In this thesis, I aim to expand the role of Nature in Design and digital fabrication by investigating *distributed* fabrication strategies for the production of constructs that are, at once, large in scale and materially tunable. I define 3 'modalities' by which to address Nature, namely: (1) *Stimuli as Input*—utilizing the natural environment (*e.g.* solar energy) as the driver for the fabrication process (2) *Matter as Output*—utilizing physical material products produced by biological organisms, such as silk or honey; and (3) *Organism as Compiler*—utilizing a biological organism as a fabrication 'agent', designed to 'govern' the fabrication process.

Figure 1.4: Silkworm fabricating 'skin' on Silk Pavilion structure. Image: Steven Keating, Mediated Matter

Stimuli as Input: Inputs categorized as 'stimuli' can include such ingredients as sunlight for direct conversion to heat, or wind as a kinetic input, or nutrients for a biological system—or any combination thereof. Termites, for example, require nutrition for survival, while sunlight provides valuable information for orienting their built structures, and wind is harnessed to create venting systems (Turner 2000). Similarly, bees take sunlight and other factors as navigational guides (Rossel 1993) such that energy becomes the input (*e.g.* the 'data') for their construction strategy and orientation; (2) *Matter as Output:* Outputs categorized as 'matter' can consist of naturally occurring chemical reactions, including an organism's production of material such as silk, or the growth of a plant. However, the output may not only be the material itself but also its spatial form (and function), derived from sensing the input(s); (3) *Organism as Compiler:* The organism *is* the translator, converter or compiler, providing the logic, or synthesizing material and energy. Whether discussing bacteria, ants or humans, the organism acts as a 'compiler' of energy and matter via a system's logic (rules), sensing, and/or through the physical mediation of matter. Insects, too, have for centuries been studied for their abilities to produce sophisticated materials such as silk (Zhao et al. 2005), or for their social behaviors (Hölldobler and Wilson 1990). Such social behaviors can specifically be found in eusocial insects, which exhibit social behavioral structures within colonies (Plowes 2010). For the purpose of this research, the subset of insects selected is of great significance, as they combine all three modalities, namely: energy as input, matter as output, and organism as 'compiler' (set within a distributed swarm configuration). The very concept of organismic colonies compiling energy and matter into fabrication output—found in ants, bees and termites—provides a wide range of powerful case studies found in Nature, that are of importance and inspiration for digital fabrication strategies. Such systems point towards potential benefits over conventional digital fabrication tools—as they offer adaptability *during* the fabrication process, they are more robust through the distribution of tasks, and they have the potential to build on much larger scales, in comparison to machine scale. However, while most of these distributed systems found in Nature—e.g. bees, ants and termites—build with homogeneous materials such as wax, clay, and sand, other non-communicating material fabrication systems (i.e., insects) can be found in Nature that exhibit very high degrees of material tunability, such as silkworms and spiders. The merging of the two may unite the best of both worlds—communicative adaptive fabrication processes with material tunability. This is the subject, and indeed the overarching goal, behind this thesis.

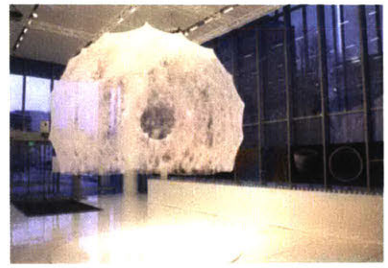

Figure 1.5: Silk Pavilion in the MIT Media Lab lobby. Image: Steven Keating, Mediated Matter

Figure 1.6: Synthetic ant environment, robotic arm UV path guide control.

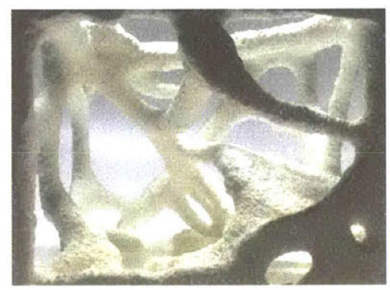

Figure 1.7: Cast of synthetic ant environment after robotic guiding procedure.

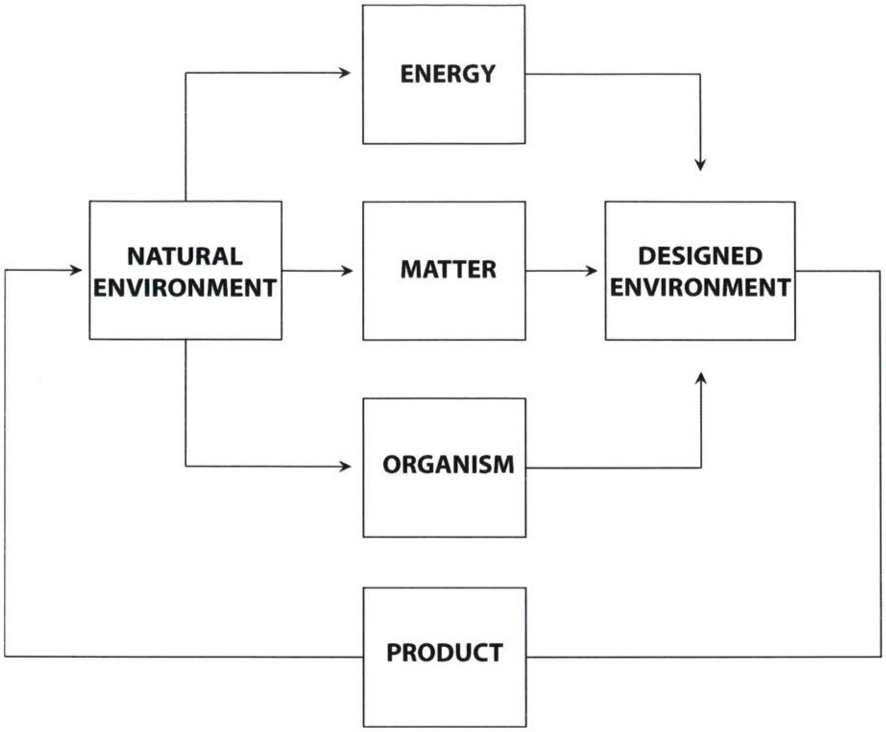

Figure 1.8: Left: Diagram of Energy, Matter and Compiler going through a designed environment producing a product from the natural environment.

1.4 Energy, Matter and Organism: Mapping the Discourse

As illustrated in Figure 1.8, the three strategies listed above—Energy, Matter and Compiler—can be defined in the context of the natural environment, but they can also be designed. This figure offers a general schema for transitioning between natural and manmade strategies, within a *designed* environment.

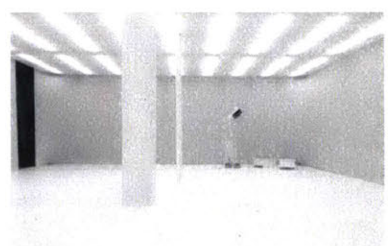

Figure 1.9: 'Synthetic Apiary', synthetic enviroment built for *Apis mellifera*.

Figure 1.10: Bees building honeycomb wax structures inside SA. Image: Sunanda Sharma, Mediated Matter

1.5 Thesis Outline

This thesis is divided into eight chapters. The first chapter introduces the relationship of Design and Nature and the role Nature plays in the historical discourse of design.

The second chapter discusses the background and research in related fields of this multi-disciplinary PhD work. First, a brief history of digital fabrication is presented and advances in digital fabrication on the architectural scale are introduced. Further, previous related work is highlighted in the context of Nature as input, output, and compiler. Finally, distributed fabrication in the research fields of biology, robotics and computer science is discussed.

The third chapter presents the vision, aims, and goals of this research, and lays out the problem definitions.

The fourth chapter discusses work leading up to the distributed fabrication ideas, evaluates the success of previous projects in mimicking natural processes digitally, and discusses advances and limitations.

The fifth chapter introduces the research framework in theory comprised of the four research thrusts: Biological Templating for Design, Technological Templating for Biology, Biological Augmentation for Design and Technological Augmentation for Biology.

This is followed by the sixth chapter, which reviews the research projects and provides practical demonstrations of some of the concepts found in the theoretical research framework in practice.

The seventh chapter delves into a detailed description and discussion of the final project—Fiberbot. A history of the development of the robotic system is discussed, followed by an in-depth description of the Fiberbot 'agent'. The deployment of 16 robots constructing a 4.5-meter tall structure is presented and evaluated.

The last chapter presents a discussion of the distributed fabrication paradigm in design and evaluates all findings. Further, future research and work are discussed, highlighting the merits and limitations of what has been achieved in this thesis and what may follow.

Figure 1.11: Fiberbot robot. Image: Joao Costa, Mediated Matter

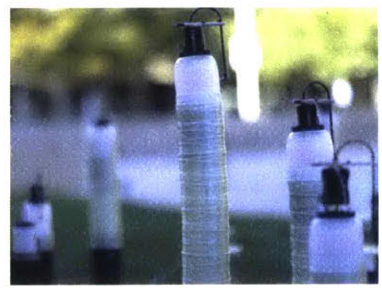

Figure 1.12: Mutiple Fiberbots building curved tubular structures.

1.6 Conclusion

Nature offers significant fabrication strategies to inform digital Design and fabrication; with some of the most fascinating and advanced strategies found in eusocial insects. Other, non-communicating insects provide examples of highly sophisticated material systems, with properties still unachievable in current material production. These examples and related strategies set the stage for this research.

Figure 1.13: The Silk Pavilion during fabrication. 6500 silkworms were deployed to fabricate the skin on a CNC fabricated scaffolding structure. Image: Steven Keating, Mediated Matter

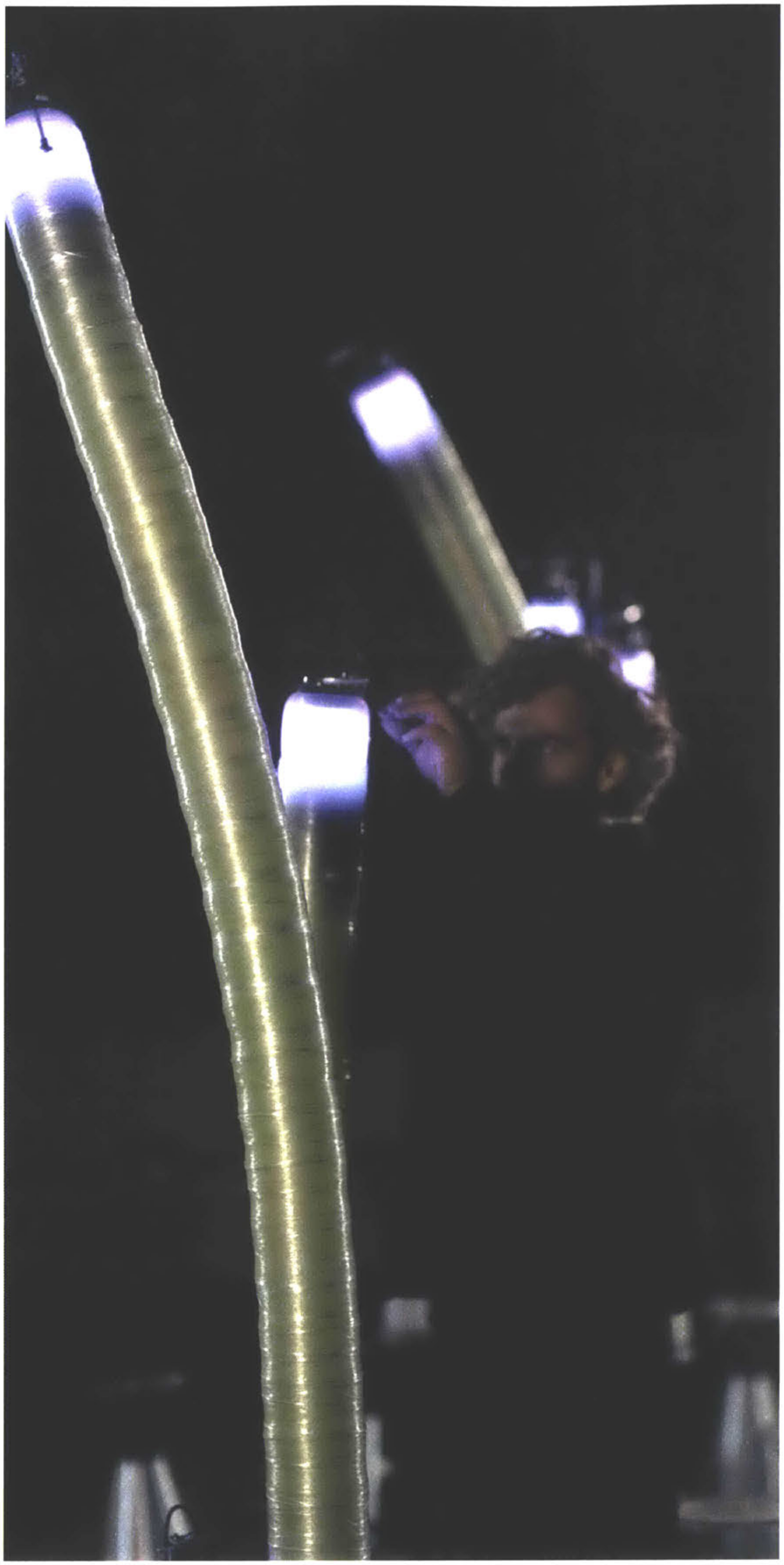

Figure 1.14: Fiberbot building tubular structures at night. Image: Joao Costa, Mediated Matter

Chapter 2

Background & Research Area Definition:
Distributed and Materially Tunable Fabrication for Digital Design

2.1 Introduction

2.1.1 The Role of the Designer

In the past, designers have been largely concerned with the form and function of a final outcome, drawing from advances in science and technology to translate what already was technologically feasible into a product. However, today more and more designers seem to have left the path of pure aesthetics in order to be directly involved in the development of processes for fabrication. For these designers, the process becomes the primary objective, rather than the final product outcome. In science, this might be called research, which often emphasizes progress toward a larger, significant goal, rather than finished product outcomes. In process design, the product *is* the process—something that cannot be purchased, but rather serves as a vehicle to demonstrate a potential. This fairly new phenomenon in design practice may be a direct result of the digital age, where information is readily and always available only a click away, thus opening the doors for all creative minds to become researchers of their own accord/in their own right.

Maybe a general trend can be observed as disciplines are collaged and merged in ways that only become possible within a larger, global social and very importantly digital network(s).

This research spans many disciplines, including research in digital fabrication, biology, robotics and computation, under the overarching umbrella of design. In the following sections of this chapter, I will discuss related work in these varying disciplines, which this thesis is inspired by, draws from and builds upon.

2.1.2 A Brief history of Digital Fabrication

2.1.2.1 The Advent of Digital Fabrication in Design and Architecture

When referring to digital fabrication tools and machines used in design and architecture, the most common are laser cutters, CNC mills, water jet machines and 3D printers. In recent years, robotic arms have been installed in the workshops of design and architecture schools. These tools not only provide a way to prototype faster and more reliably, but also enable the creation of new digital tools that allow novel methods of fabrication and design. The robotic arm is a particularly interesting addition to this space, as it provides a 6-axis motion platform without any direct affordance, meaning it may serve any fabrication application in 3D space.

In order to review the latest developments in digital fabrication in design and architecture today, I want to briefly turn to history to understand where these tools came from.

When John T. Parsons invented the first numerically controlled (NC) milling machine at MIT in 1958, it still used punched paper tape to store the tool path and was meant to automate the complex fabrication of helicopter rotor blades (Younkin and Hesla 2008). The first 3D printing machines came to market in the 1980s, providing the ability to create objects with internal features only possible with additive manufacturing (AM) (Hull 1986). Many different AM methods followed using the same basic principle of adding materials in layers, innovating on materials and processing of materials. The UNIMATE, the first robotic arm, was introduced in 1958 and soon after deployed in the car industry (Hockstein et al. 2007). Interestingly, this technology went straight to industrial application and much later was adapted from industry into the hands of designers and architects. As this technology was not a fabrication technology but rather a digital positioning platform, it was ready to be deployed in industries that do not deal with the challenges of materiality. 3D printing mainly started as a rapid prototyping protocol, as the materials that the early printers could use were mostly nonfunctional, brittle polymers. Hailed by many as a revolution for fabrication, 3D printing is really only a welcome addition to the digital workshop, complementing but not replacing the palette of other digital processes (Gershenfeld 2012). Even though the digital fabrication revolution is well on its way, there are plenty of opportunities for designers to step in and change, adapt, or even invent novel processes in terms of materials and digitally controlled handling and processing of these materials.

2.1.3 Large-scale Digital Fabrication in Design

Many designers and architects are turning towards research in digital fabrication technologies, as they may provide valuable new methods and applications for the built environment. Experimental and forward-looking digital fabrication has had a great impact on this field, allowing experimentation on the architectural meso scale—referred to in architecture as pavilions or large-scale installations. Here, I will review a few of those projects, which are either concerned with large-scale 3D printing, or which use robotic arms as positioning platforms for new fabrication processes (Naboni and Paoletti 2015).

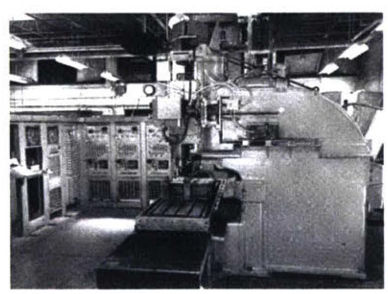

Figure 2.1: The first numerically controlled milling machine built at MIT. Image: (Pease 1952)

Pioneering the field of architectural applications of the robotic arm are the architectural duo Gramazio and Kohler at the Eidgenössische Technische Hochschule (ETH) in Switzerland. Their innovative use of a very common material and technology—bricks and an industrial robotic arm—has literally brought waves into walls. An end effector was designed which can lift and place (release) bricks, thus giving a tradition thousands of years old a digital counterpart. This digitalization (automation) of bricklaying made advanced forms possible.

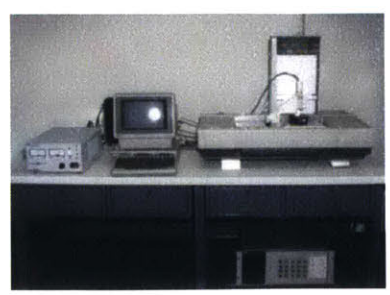

Figure 2.2: First stereolithography 3D printer, the SLA 1. Image: (Krassenstein 2015)

Another interesting project related to the use of robotic arms, but using a more sophisticated material system (namely fiber composites), is led by Achim Menges at the University of Stuttgart, Germany. This pavilion structure is built by rotating a large scaffold radially, while a robotic arm applies fibers and resin at hooks located on the spinning scaffold (Reichert et al. 2014). This project demonstrates an interesting shift from basic block assembly to a more continuous and materially tunable approach in architectural digital fabrication. However, in this approach, large and structure-specific scaffolds are still required. Yet another project making innovative use of the robotic arm in design is a project by Joris Laarman in collaboration with the Institute of Advanced Architecture of Catalonia, Spain. This project uses a two-compound heat cured epoxy extrusion to print in free space. Free-form printing advances the field as it functions without a scaffolding structure or support material, creating curved rod structures (Laarman 2017).

In the race to 3D print large-scale architectural components, many advances have been made in the last decade. A Chinese company, Winsun, prints concrete components in 2.5 D (without support material and overhangs) and assembles the components in post, building multistory houses (Sevenson 2015). Contour Crafting is another project proposing a very large gantry system to build full scale houses (Khoshnevis 2004) and is now a company promising concrete 3D printers to roll out in 2018 with the aim to build houses, infrastructure and space habitats (Contour-Crafting-Corporation 2017).

Yet another promising approach to large-scale 3D printing is found in the Digital Construction Platform by Steven Keating from the Mediated Matter group at the MIT Media Lab, led by Neri Oxman. This project uses a combinatorial method that mixes free-form printing and the commonly applied 2.5 D approach. The printed polyurethane foam doubles as the insulation layer and thus providing a fast way to print as well as the ability to print horizontally as the foam spray attaches, expands and cures in seconds. An open dome structure 14.6 meters in width by 3.7 meters in height was built in only 13.5 hours, demonstrating the system's ability in speed and special parameters (Keating et al. 2014, Keating et al. 2017).

Overall, advances in this field have been manifold and will continue to challenge scale and material sophistication. However, when it comes to varying materials on the fly as well as further scaling up these systems, it becomes apparent that the majority of the described systems already operate at their limit in scale and thus provide no real answer to the automation of even larger-scale construction, leading into projects built at the architectural scale without pre-fabricated parts, as seen from the company Winsun. This leads to the next section, which looks at state-of-the-art research on swarm robotics and distributed fabrication paradigms to be explored in this thesis through the lens of design.

Figure 2.3: 'Unimate': first robotic arm presented on the Tonight Show, 1966. Image:(Robotic-Industries-Association 2017)

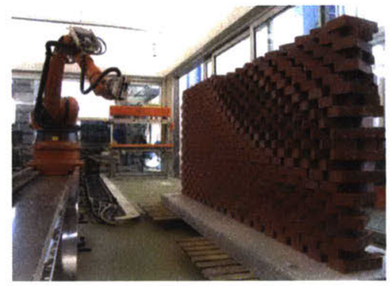

Figure 2.4: 'Fabrication of Wall', Robotic assembly of wall at ETH Zürich, Switzerland. Image reprinted from: (Bonwetsch et al. 2006)

Figure 2.5: View of robotic winding process. Image reprinted from: (Reichert et al. 2014).

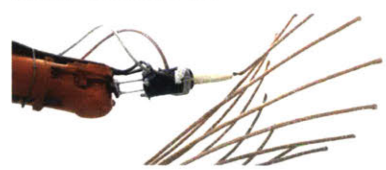

Figure 2.6: The 'MX3D-Resin' project, robot draws/extrudes material in free space. Image source from: (Laarman 2017)

2.1.4 Introduction to Swarm Robotics and Distributed Fabrication

The past decade has seen various advances in *swarm robotics* dedicated to algorithmic control and robotic engineering (Bayindir and Sahin 2007, Beni 2005, Cianci et al. 2007, Dorigo 2005, Dorigo and Sahin 2004, Dorigo et al. 2005, Ladley and Bullock 2004, Mondada et al. 2005, Niu, Zhu, and He 2005, Petersen, Nagpal, and Werfel 2011, Pinciroli et al. 2011, Stewart and Russell 2006, Winfield, Harper, and Nembrini 2005, Zhang and Xing 2010). The field of *swarm construction*, however, has not been yet able to demonstrate actual structures built by multiple robots utilizing stochastic swarm behavior.

Previously realized structures using robotic swarms are commonly constructed out of predefined building components—such as rectangular polymer blocks or extruded aluminum sections. These building components are typically connected by previously applied additional parts, such as magnets or glue strips (Bayindir and Sahin 2007, Dorigo 2005, Dorigo et al. 2005, Ladley and Bullock 2004, Lindsey, Mellinger, and Kumar 2011, 2012a, Mondada et al. 2005, Parker, Zhang, and Kube 2003, Petersen, Nagpal, and Werfel 2011, Pinciroli et al. 2011). The *TERMES* project—developed at the WYSS Institute at Harvard University—represents the state of the art in current swarm construction (Petersen, Nagpal, and Werfel 2011, Werfel, Petersen, and Nagpal 2014). Researchers developed a robotic material system reliant on gravity to autonomously build a structure from rectangular blocks. The 10-block structure can build a staircase and the robot is capable of climbing up the structure, picking up blocks, and placing these blocks according to a predefined Design. Similarly, the SWARM project developed at the University of Pennsylvania demonstrates the construction of structures made of cubic scaffolding assemblies using flying robots called 'quadrotor teams'. These robots are equipped with mechanical grippers that can pick up square tubular components with magnetic connection pieces (Lindsey, Mellinger, and Kumar 2011). The 'Flight Assembled Architecture' project was developed by Professors Raffaello D'Andrea, Matthias Kohler, and Fabio Gramazio at ETH Zurich. To date, this project is the first of its kind, building a large-scale structure (6 m in height) utilizing flying robots ('quadrocopters'). The robots pick up lightweight polymer bricks and stack them in a controlled environment according to a previously designed computer model. A deterministic approach is taken, as the material blocks are generically defined and connections are prepared prior to block pick up. The flying robots act collectively within a defined path, not collaboratively as individuals, according to swarm intelligence (Willmann et al. 2012, Willmann et al.). To summarize: the area of investigation provides a wealth of research in related fields of distributed fabrication and design in biology, robotics and computation. The study of biological distributed systems—specifically of eusocial insects—has shaped a field in computation for optimization through Nature inspired algorithms, which in turn is greatly reflected in robotic research. However, current examples in robotic distributed systems for fabrication generally deal with the assembly of self-similar prefabricated parts or self-assembly of the robots themselves. As examples of distributed fabrication systems for material tunability are scarce, this is where this thesis seeks to establish novel research.

Figure 2.7: Illustration of the 'Contour Crafting' large-scale 3D printing method. Image source from: (Scott 2017)

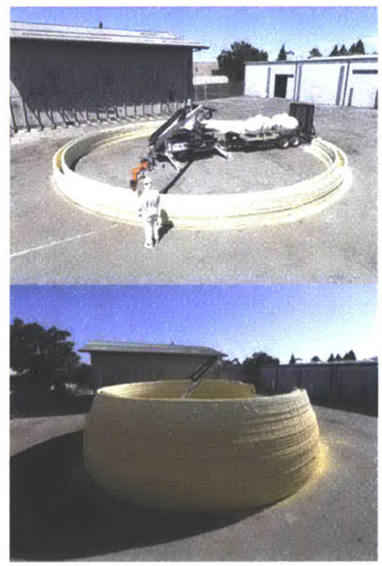

Figure 2.8: The 'Digital Construction Platform' building a dome. Images adapted with permission from the author: (Keating et al. 2017)

2.2 Design Fabrication in Past Projects & Case Studies

2.2.1 Nature as Fabrication Input

In Design practice, there have been numerous examples for including Nature as the main energy 'input' for the fabrication of objects. The *Sun Cutter* project (Kayser 2010) uses focused sunlight to cut thin sheets of plywood to produce sunshades. Here, the metaphor and direct application of Nature's affordances comes into play. In a similar way, Merel Karhof's *Wind Knitting Factory* (Karhof 2011) explores the metaphor and direct use of Nature as energy 'input'. Here, wind is used to actuate a knitting machine to produce scarves. Once again, whether we are discussing sunshades produced by sunlight, or a scarf made from wind, these *more-poetic-than-functional* Design projects hint at the transitioning of Design from pure metaphor—represented largely in aesthetic and formal language—towards metaphor in the way things are actually produced. Designers are beginning to include Nature as a source of energy for production.

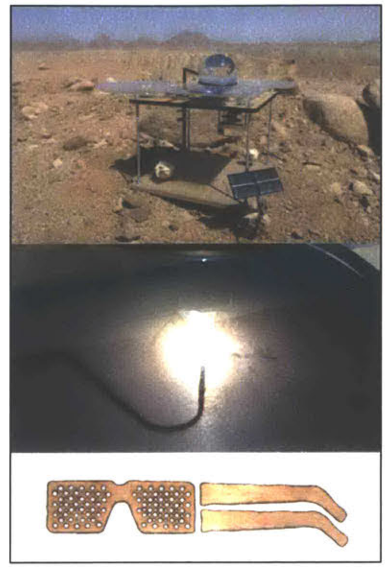

Figure 2.9: Sun Cutter machine, focal point, and sunshade product.

2.2.2 Nature as Fabrication Output

The *Solar Sinter* project explores how Nature can provide both the input and the output for digital fabrication (Kayser 2011-12). This project takes solar radiation and sand from its immediate environment—the desert—to produce glass objects. The output comes from Nature and over time could also be fed back to her. This project already embodies two of the three modalities: Nature as input, and as output. Here, the 'machine or 'compiler' is a purely digitally controlled, electromechanical platform feeding off of Nature. Another example found in Design is Tokujin Yoshioka's *Spiders Thread*, in which the artist uses the process of crystallization to produce a chair via a thread scaffold (Yoshioka 2013). Here, the fabrication output is formed via a chemical reaction being defined by natural Design.

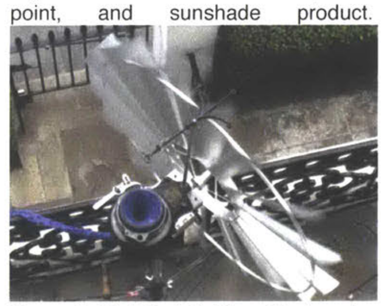

Figure 2.10: Wind Knitting Factory by designer Merel Karhof. Image source: (Karhof 2011)

The Solar Sinter machine (Figure 2.11) is based on the mechanical principles of a 3D printer. A large Fresnel lens (1.4 x 1.0 meter) is positioned with its focal point directed at the center of the machine and at the top of a sand box where an object is built up layer by layer. Photovoltaic panels provide the electricity required to drive the motors and electronics of the entire machine. The lens focuses a beam of light that produces temperatures between 1400°C and 1600°C to melt the sand into glass.

This project demonstrates the ability to create energy-efficient fabrication technologies in conjunction with abundant natural resources. This clear demonstration of the potential of natural materials and energies may be applied to swarm robotics as well. Self-sufficiency is key in robust autonomous systems, whether used as a guide for biological systems or construction robots. I aim to develop this kind of truly self-sufficient fabrication approach on multiple scales.

Figure 2.11: The Solar Sinter machine, focal point, bowl product.

2.2.3 Nature as Fabrication Compiler

'Compiler' in Nature can take many forms. Whether a silkworm compiles material and lays out a deposition pattern in a figure-eight-configuration, a caddis fly larvae compiles grains, pieces of shell, and silk fiber into a cocoon, or a bird carefully crafts its nest, Nature is full of examples. The *Honeycomb Vase* (Libertiny 2013) by Tomáš Libertíny is a great example of the organism as the compiler, where the designer intervenes with a desired result in mind. A preformed wax structure is given to the bees, who complete it and make it whole. The assembled predefined structure—in this case a vase—is co-fabricated by the bees, making it a seamless object. Here, the bees are used in their natural capacity, with their ability to create honeycomb structures—by simply altering their environment spatially, they compile an object in the designer's preferred form.

Figure 2.12: 'Spiders Thread' by Tokujin Yoshioka. Image reprinted with permission from the artist: (Yoshioka 2013)

The artist Hubert Duprat has used caddisfly larvae as the compiler of his work. While caddisfly larvae usually inhabit streams and lakes, and assemble the grains of sand and pieces of debris that surround them into protective cases, Duprat took them out of their natural environment and gave them gold nuggets, precious stones and pearls to assemble, resulting in a product outcome (Duprat 2007). But organisms can also serve as compilers in less direct ways, giving inspiration to algorithms for optimization or distributed robotics—in some cases the organismic compiler may purely provide the logic. The environmental conditioning of the biological compiler is at the heart of most of these fabrication experiments. Behavioral change comes from modifying the environment for a specific Design and fabrication output. By modifying the material system, spatial environment and/or other environmental factors such as light, humidity, or temperature, organisms with already-existent fabrication output can be manipulated to produce more closely what we desire. This leaves the metaphor of Design behind for a more direct application of Nature's affordances in terms of the energy, material, and organism.

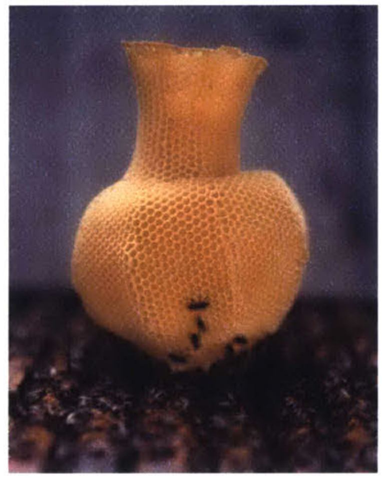

Figure 2.13: 'The Honeycomb Vase' courtesy of MoMA. By the artist Tomas Libertiny, 2006. Image: photo credit: Raoul Kramer (reprinted with permission from the artist)

2.3 Distributed Fabrication Paradigms in Related Research

2.3.1 Biology

Collective behavior is a phenomenon found in social insect species such as ants, termites and bees, and also in schools of fish and flocks of birds. The fascination lies in the collective intelligent behavior of large numbers of 'simple', self-similar individuals communicating only on a local level yet achieving collective coordination, acting as a single large organism (Kennedy and Eberhart 2001). Among social insects, chemical sensing often provides the means for communication. The production and sensing of pheromones in social insects such as wasps, bees, ants and termites are a huge area of research in understanding swarm behavior (Vander Meer et al. 1998).

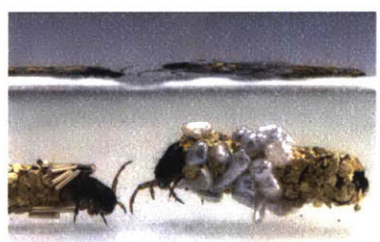

Figure 2.14: Artist Hubert Duprat's work on cofabrication with caddis fly larvae. Image source: (Duprat 2009)

Also, marine organisms such as corals and siphonophores can live in colonies and collectively act as seemingly single larger organisms. Particularly, the group of siphonophores are interesting species with examples of colonial self-organization, where individuals within the colony develop varying functionalities e.g. catch prey or defend the colony from other predators, and cannot survive as individuals without being attached to the colony. These species can form some of the world's longest organisms, reaching up to 50m in length. (Mapstone

2014)

2.3.1.1 Distributed Additive Fabrication in Nature

Distributed additive processes can be observed in the formation of the termite mound, specifically *Macrotermes jeanneli* which have been studied and successfully bred in the laboratory (Leuthold, Triet, and Schildger 2004).The termites collectively build structures that are orders of magnitudes larger than an individual termite, with populations reaching up to millions of individuals. The mounds are highly adaptive, incorporating multifunctional enclosures for breeding, farming 'crops' in the form of fungi and as shelter, with emphasis on climate control in accordance to the natural environment surrounding the mound (Turner 2000). Bees and wasps provide further examples of additive fabrication via a collective system of small agents. Bees not only assemble but produce their building material through their wax glands. The wax is then deposited in a repetitive packed hexagonal pattern, which is endlessly copied in synthetic material fabrication and design for its superior structural properties to weight ratio (Gibson and Ashby 1999). Bees are highly communicative within the colony (waggle dance, pheromones) and share tasks according to a hierarchical system based on age (Munz 2005). Environmental factors have a great effect on the bee colonies, which have been connected to the decline in population of honeybees in the last decade. Like ants or termites, bees have often been referred to as a 'super-organism': tens of thousands of individual bees can form a single hive colony without a chance of individual survival (Hölldobler and Wilson 2009).

Figure 2.15: Cathedral Termite Mound in the Northern Territory. Photo taken and supplied by Brian Voon Yee Yap (Yap 2006)

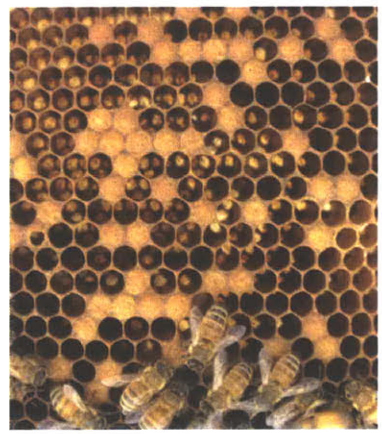

Figure 2.16: *Apis mellifera* honeycomb structure.

Other examples of swarm behavior and distributed construction in the natural world are observed within the micro-organismic milieu—including slime mold and bacteria. In the case of the latter, there has been extensive research in the past two decades on multicellular organization. James A. Shapiro has proposed that we think of 'bacterial populations as multicellular organisms' (Shapiro 1998), which interact by means of molecules, generate gene expressions, and share tasks in organized patterns, all of which—in turn—promote the survival of the colony. So potentially, when thinking of hierarchical material organization for spatio-temporal tunability, another distributed functional micro-scale layer of fabrication could be added.

Figure 2.17: 'Carpenter Ants in a Tree', *Camponotus pennsylvanicus.* Kenilworth Marsh. Washington, DC, USA, Image: Katja Schulz (CC BY 2.0) (Schulz 2012)

2.3.1.2 Distributed Subtractive Fabrication in Nature

Ants are some of the most notorious communal builders, but with a different strategy compared to the above. Ants mostly use a *subtractive* approach to fabrication creating intricate tunnel networks sometimes spanning many cubic meters in scale (Wirth et al. 2013). While in digital fabrication e.g. CNC-milling, the subtractive fabrication approach may seem quite limiting due to the gantry's or robotic arm's physical dimensions and thus being mainly restricted to surfaces, in Nature the subtractive approach becomes highly interesting in distributed systems where these limitations do not apply, as 'agents' or fabrication nodes do not have any attachments points and can roam freely through a material and thus being able to achieve similar complexity levels compared to the additive fabrication approach.

2.3.2 Robotics

In robotics, there are multiple attempts to build distributed robotic systems for fabrication. The following will take a closer look at some of the advances in this field.

2.3.2.1 Distributed Fabrication Through Discrete Part Assembly

Most of the research is demonstrated in the assembly of discrete parts into three-dimensional structures. The *Termes* project by the Self-organizing Systems Research Group at Harvard University is an autonomous robotic construction system, assembling prefabricated stackable 'bricks' using small robots, which can pick up and carry the 'bricks' as well as climb the resulting structure (Petersen, Nagpal, and Werfel 2011). This project may be classified as being advanced in terms of autonomy and communication but lacks any material tunability or sophistication as the resulting structure is an assembly of bricks held together by gravity without functional material properties required for a structurally sound three-dimensional construction. Another example can be found in the collaborative effort of architects and computer scientists at ETH Zurich (Augugliaro et al. 2014), who are using quadrocopters to assemble foam bricks in a centralized construction approach. What is impressive about this project is the sheer scale that was achieved—reaching six meters in height. As there was no communication between 'agents', but defined path trajectories were given to the drones that were assembling the structure brick by brick, this project is distributed. Multiple agents were actively involved in the assembly, although a single unit could have achieved the same outcome over a longer time frame. Also, the material system—foam blocks and adhesive—does not lend itself to structurally sound architecture, and also lacks any potential for material tunability.

Figure 2.18: Wood carved by carpenter ants.

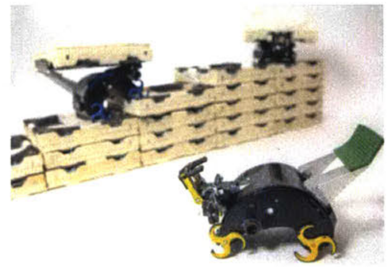

Figure 2.19: The Termes project Image: Eliza Grinnell, SEAS Communications. Image reprinted from: (Werfel, Petersen, and Nagpal 2014).

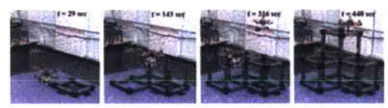

Figure 2.20: 'Construction of Cubic Structures with Quadrotor Teams' developed by (Lindsey, Mellinger, and Kumar 2012b).

In terms of material approach similar limitations can be found in Vijay Kumar's work with distributed assembly of magnetic components into cubic structures by quadrocopters. However, in contrast to the 'flight assembled architecture' project from ETH, Kumar's approach focuses on autonomous behavior of the drones and actually succeeds without a completely centralized system or preplanned path trajectories (Lindsey, Mellinger, and Kumar 2012b).

Figure 2.21: 'Flight assembled architecture' developed by (Augugliaro et al. 2014)

All of these distributed robotic fabrication approaches share an absence of material tunability or sophistication, with varying degrees of intercommunication within the fabrication nodes. Another relevant approach to robotic fabrication is the robotic assembly of *'digital material'* by the Center for Bits and Atoms at MIT (Gershenfeld et al. 2015). Here, researchers attempt to assemble large-scale, mass-produced (injection molded) triangular parts into a robust and lightweight cellular structure with a climbing robot. While this approach also lacks material tunability, it provides the potential for disassembly and alteration over time. Although the assembly robot has not yet been deployed in any distributed manner, it still has interesting temporal material features.

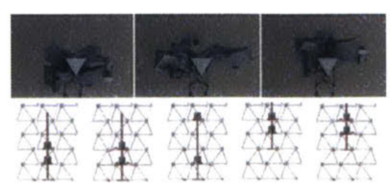

Figure 2.22: Simulated assembly of 'digital material' by the Center for Bits and Atoms at MIT. Image reprinted from (Gershenfeld et al. 2015).

2.3.2.2 Distributed Fabrication Through Continuous Material Deposition

When it comes to amorphous materials with the potential to be graded spatially, there are few examples of distributed robotic fabrication systems. The *Minibuilder* project by designers Jokić and Novikov uses robots to lay down a heat-curable epoxy compound additively with the robot driving on the build structure (Jokić et al. 2013). A secondary robot can climb vertically on the sidewall of the structure, adding another layer of the same material. No feedback or communication between fabrication nodes nor autonomous behavior within a fabrication node was realized, thus making it merely fit the category of distributed fabrication. But since it is a clear attempt at tackling large-scale fabrication by multiple robots, it still is relevant to discuss and explore in the context of this thesis. The Self-organizing Systems Research Group at Harvard University has also executed a project relevant in this context. The group has built and tested a foam-extruding and ramp-building robot (Napp and Nagpal 2014), which is entirely autonomous. However, while this robot possesses advanced autonomy regarding its sensing capabilities as well as its ability to compute results for decision-making, its material system and deposition approach lack any potential for building at large scale with spatial tunability.

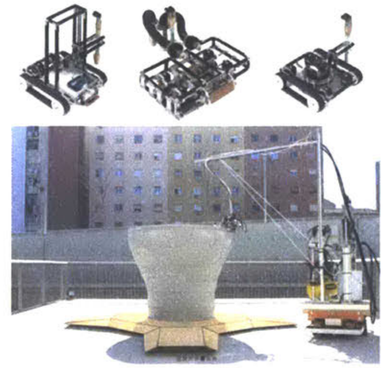

Figure 2.23: The 'Mini Builders' project. Top: building robots, bottom: construction of large scale vessel. This project was developed by Sasa Novikov and Petr Jokic at the IAAC (Jokic et al. 2014, Jokić et al. 2013).

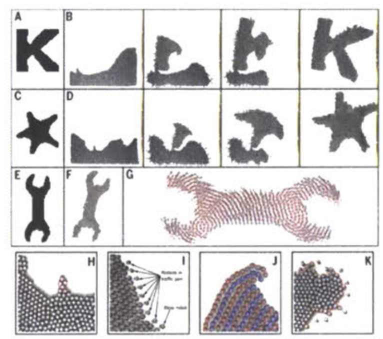

Figure 2.24: Self-assembly experiments using up to 1024 physical (KiloBots) robots. This project was developed by (Rubenstein, Cornejo, and Nagpal 2014)

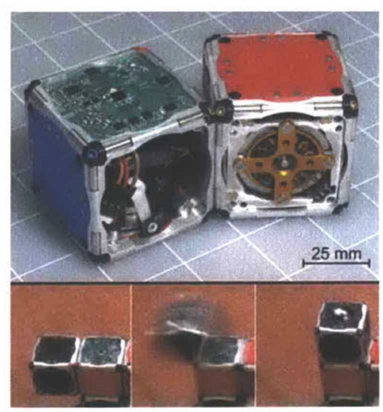

Figure 2.25: 'M-Blocks' developed by the Distributed Robotics Lab at MIT. (Romanishin, Gilpin, and Rus 2013)

2.3.2.3 Distributed Fabrication Through Self-Assembly

Self-assembly robots are another category in the field of distributed fabrication where robot and material unite and essentially become compilers of themselves (Mehta et al. 2014). Two-dimensional approaches to self-assembly robots have been tested in research. It was shown that up to a thousand robots can form two-dimensional shapes autonomously with only local communication (Rubenstein, Cornejo, and Nagpal 2014). While this is indeed impressive—at least in terms of the sheer number of robots working cooperatively—the robots do not actually assemble, but rather form a pattern on a two-dimensional surface. Under these circumstances, the term fabrication can hardly be applied. However, three-dimensional structures built from cubic robotic building blocks have also been achieved. These building blocks are held together by magnetic force and are built by disassembly (Yim et al. 2007, Gilpin, Knaian, and Rus 2010), widely falling under the subtractive method of digital fabrication. One of the most interesting and realized robotic self-assembly projects is *M-Blocks* from the Distributed Robotics Lab at MIT CSAIL. These cubic robots can assemble additively and subtractively by spinning and braking a flywheel for locomotion, and are able to climb and move across a structure as well as attach and detach via permanent magnets (Romanishin, Gilpin, and Rus 2013). In the future, such approaches to distributed fabrication may have benefits over other digital fabrication systems, as structures can morph over time; however, spatially the scale of parts limits the designs, with no variation in material properties, thus making miniaturization key for more freedom in the design of such structures. Robotic self-assembly can provide valuable insight into how to think about the temporal dimension in distributed robotic systems, as actuation of material and the material itself are inseparable.

2.3.3 Computation

When it comes to distributed robotic fabrication approaches, the computational research landscape may be categorized into centralized and decentralized approaches (Yan, Jouandeau, and Cherif 2013, van Den Berg et al. 2009, Wagner and Choset 2015, Luna and Bekris 2011). Centralized computational approaches are often used in situations requiring predictable high-level behaviors and theoretical guarantees on optimality. In practice, this leads to the deployment of at least one omniscient agent that essentially plans for all the other agents, and—due to the computational complexity—often requires relaxation of the optimality guarantees (Lindsey, Mellinger, and Kumar 2012b, Augugliaro et al. 2014). Decentralized approaches, on the other hand, encode local per-agent decisions with limited information sharing among the agents. This approach is often simpler to implement and scales well for many agents, but it tends to be more difficult to predict and to control high-level behaviors. Subcategories of decentralized systems are rule-based approaches. These approaches are frequently inspired by nature (Theraulaz, Bonabeau, and Deneubourg 1998, Reynolds 1999), where each agent follows a set of simple rules that govern its local behavior, and are popular due to their ease of implementation and scalability (Petersen, Nagpal, and Werfel 2011, Rubenstein, Cornejo, and Nagpal 2014). Most algorithms fall under the above two categories, but many are beginning to merge concepts from both (Turpin et al. 2013, Wagner and Choset 2015). In the development of this research, communication of robots only plays a minor role, as the focus lies on the development of the hardware systems first. However, for future developments, computation will play a pivotal role and all of the above approaches will be considered 'simple' rule-based systems inspired by biological systems. Those with entirely local knowledge should be favored over a centralized approach, working towards a robust yet pliable robotic fabrication system with room for redundancy.

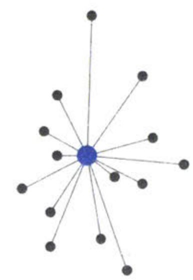

Figure 2.26: Diagram of centralized computational approach. All agents listen to a single node.

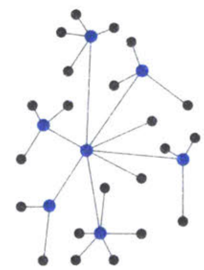

Figure 2.27: Diagram of decentralized computational approach. Local per-agent decisions with limited information sharing among the agents.

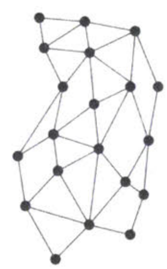

Figure 2.28: Diagram of distributed computational approach. Information is shared locally with each agent holdign equal responsibilities.

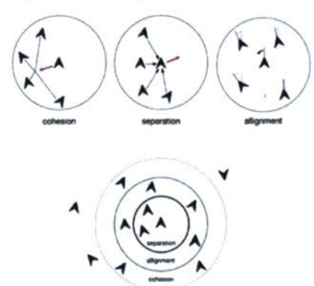

Figure 2.29: Steering behaviors for autonomous characters, Cohesion, alignment, seperation as found in flocks of birds (Reynolds 1999).

The concept of simple computer programs achieving complex (geometric) results can be traced back to what is called 'cellular automata', which history dates back to the 1940's. The basic idea is of an array of individual cells (one-dimensional in its most basic form), switching between finite states in accordance to their current and neighboring cells states. A local rule, which is identical to all cells is applied at each state switch and to all cells simultaneously in a discrete time sequence.(Sarkar 2000) In Steven Wolfram's extensive review and experiments on cellular automata he argues for a commonality in Nature and that sometimes very few rules are necessary in order to create complex natural formations. (Wolfram 2002)

"And the reason that such complexity is not usually seen in human artifacts is just that in building these we tend in effect to use programs that are specially chosen to give only behavior simple enough for us to be able to see that it will achieve the purposes we want." Steven Wolfram (Wolfram 2002)

This point Wolfram makes resonates with and is acknowledged in the ideas and work put forward in this thesis but instead of software development the point is to acknowledge and find the 'simple programs' inherent in Nature in order to tap into their genius by changing certain parameters and/or build robotic hardware capable of operating through simple rules while achieving complexity in physical output.

Emergent behavior in the natural world is a widely studied field in computer science and robotics. For example, the flocking of birds as first described in the 'Boids' program by Craig Reynolds, distills three basic rules for this emergent behavior as cohesion, separation and alignment in order to keep a general global direction of the flock, avoid collisions but also stay close enough to share aerodynamic benefits in flight.(Reynolds 1999)
Stigmergy is another form of emergent behavior and self-organization found in ants and termites. Also, in this example simple rules govern complex formations through simple 'agents'. A given path is continually strengthened, following a single ant or termite that deposits a pheromone trail after successful foraging, others follow this path increasing the pheromone trail as they successfully forage. As the food source is depleted unsuccessful foraging leads to a decrease in pheromone strength and thus an abandoning of this path. This indirect form of communication and feedback loop as in increase and decrease of stimuli has been formulated into algorithms for optimization and routing networks and path planning in robotic systems.(Dorigo, Bonabeau, and Theraulaz 2000) Nature plays a significant part in the development of algorithms in computation, while computer science can also help us to understand basic principles in Nature through finding the 'simple' rules, which can lead to such complexity and beauty.

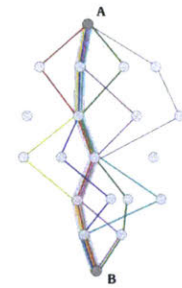

Figure 2.30: 'Find the shortest path with ACO', With an ant colony algorithm, the shortest path, in a graph,between two points A and B, emerge from the combination of several paths. Image: Johann Dréo, 2006, CC 2.0. (Dreo 2006)

2.4 Conclusion

Significant advances have been made in large-scale digital fabrication in Design. Robotic arms and the deployment of massive 3D printers has already started to change the way we think about digital construction for the architectural scale enabling new forms and functions. However, it also becomes apparent that even for these large scale-digital fabrication technologies, the maximum scale has been reached. In theory, distributed fabrication could hold answers to the question of scale.

In Design, as the case study projects illustrated above, Nature indeed can act as input in the form of energy and stimuli, as output through materials, and as compiler through organisms that construct in accordance with a designed scaffold.

Further, in Nature swarms of insect builders demonstrate that, at least in theory, this may be applicable to larger scale multi-robot systems.

However, the pre-defined nature of the substrate material characteristic to all distributed case study projects reviewed above appears to limit design strategies for relevant applications in building constructions. To this date, robotic swarms have acted merely as assemblers of pre-fabricated components. Such low-level subassemblies are typically structurally componentized and materially homogeneous. The established approach of constructing pre-manufactured building components stands in contrast to the potential of swarm construction to deliver highly customized structural and material forms able to potentially adapt and respond to environmental pressures.

Furthermore, in biology, robotics, and computation, distributed fabrication paradigms present valuable insights into how Nature can provide the strategies for fabrication, whether it is via mimicking material systems in assembly, inspiring algorithms, or through robot Design. While in biology, some systems may provide answers to questions of communication for fabrication and others illuminate approaches to advanced and tunable material systems, the robotic research helps to understand the limitations of the available technology today, such as scale and robust and tunable material properties in the fabrication output.

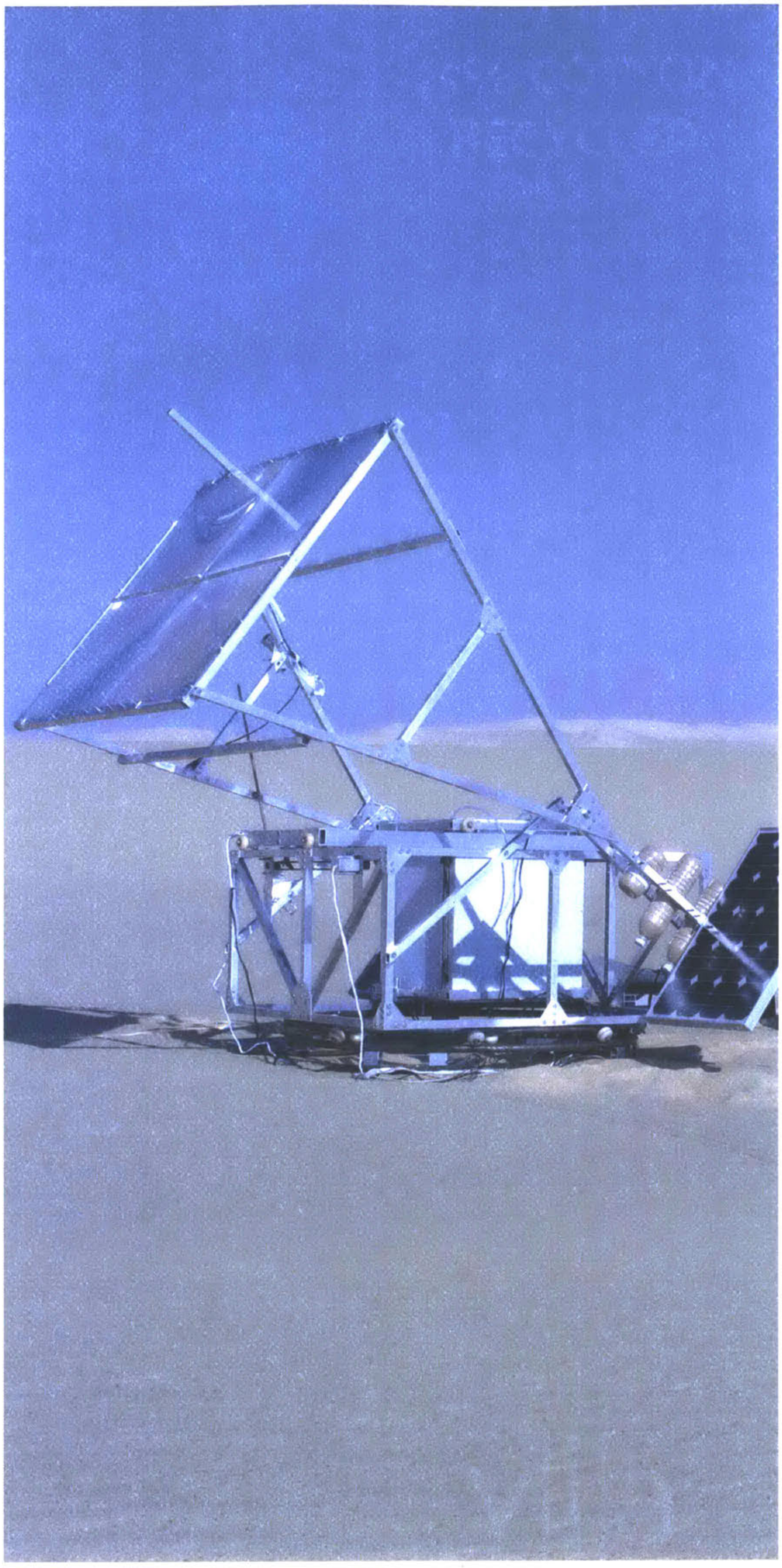

Figure 2.31: Solar Sinter in the Egyptian Sahara desert.

Figure 2.32: Solar-sinterered bowl in the Moroccan desert. Image by the author.

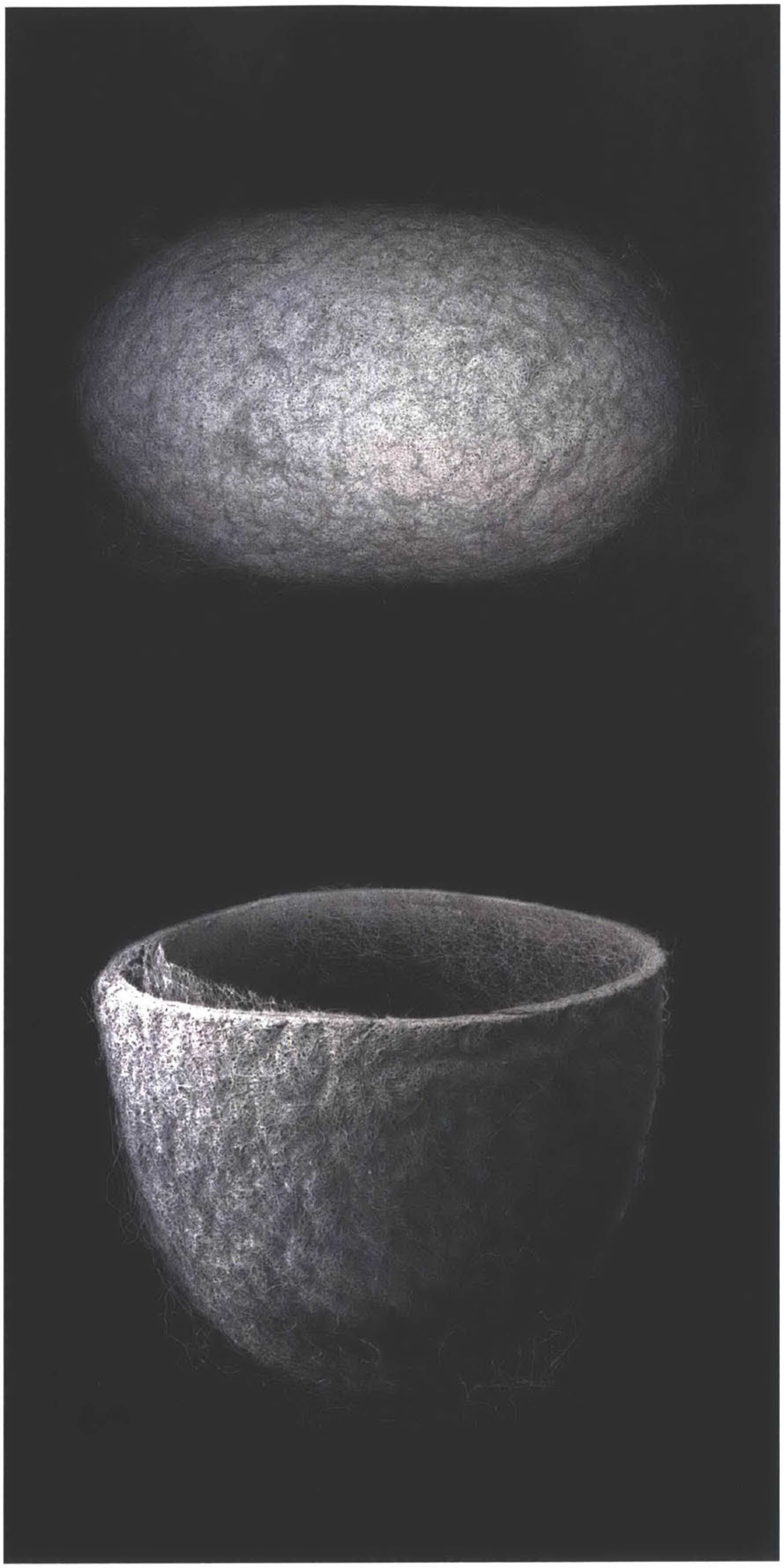

Figure 2.33: Top: 25X magnification overview SEM micrograph of a domesticated *Bombyx mori* cocoon, Bottom: 40X magnification, isometric view, SEM micrograph of an equatorially bisected domesticated *Bombyx mori* cocoon. Image taken for the Silk Pavilion project by Dr. James Weaver from the WYSS Institute, Harvard Univeristy.

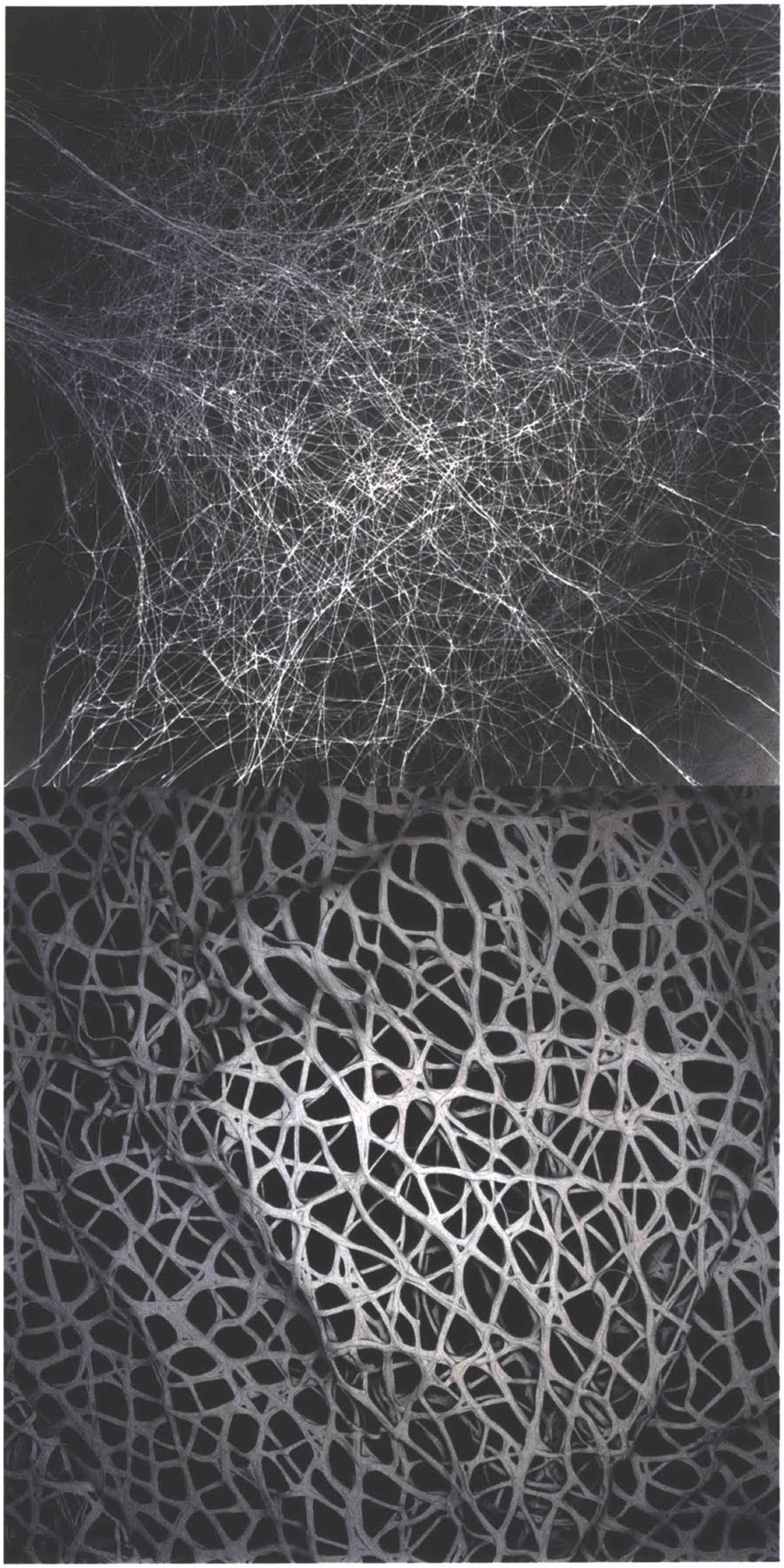

Figure 2.34: Top: SEM of *Bombyx mori* silk scaffolding structure, Bottom: SEM of 100X magnification SEM micrograph of the external surface of a wild *Antherina suraka* cocoon. Image taken for the Silk Pavilion project Dr. James Weaver, WYSS Institute, Harvard Univeristy.

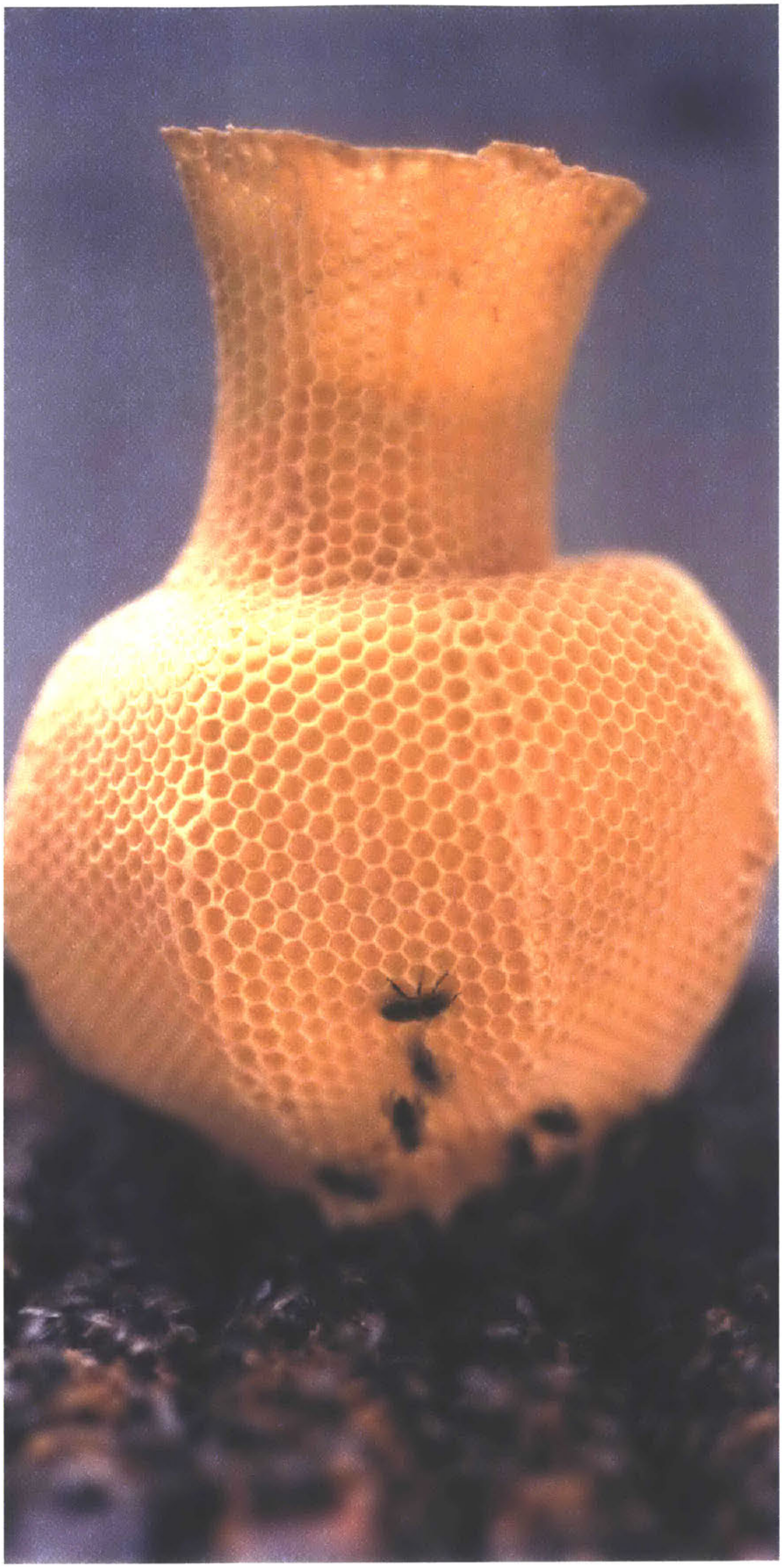

Figure 2.35: 'The Honeycomb Vase' courtesy of MoMA. By the artist Tomas Libertiny, 2006, photo credits: Raoul Kramer, reprinted with permission from the artist.

Chapter 3

Motivation
Spatio-temporal Tunability in Design

3.1 Introduction

Historically, product and building Design and construction technologies have co-evolved to complement each other. New trends and movements drive the development of construction techniques and new technologies in turn, enable designers and architects to further push the envelope of Design. Today, automated swarm and construction methods have the potential to usher in the next era of architecture. However, as discussed in the background chapter (Chapter 2) their realization on architectural scales hinges on the development of *truly scalable systems* capable of generating load-bearing structures in an efficient manner.

Current manufacturing approaches can be classified with respect to two basic attributes: (1) the level of communication between fabrication units and (2) the degree of material tunability. Until now, manufacturing paradigms were confined to *one* of these attribute axes: with certain approaches utilizing *complex* tunable material but having virtually no communication, and others assembling *simple* building blocks or pre-fabricated components in a cooperative fashion with high levels of intercommunication.(Oxman, Duro - Royo, et al. 2014)

The majority of current research efforts in swarm construction focus on the aggregation of *discrete* building components (*e.g.* blocks or beams) that mimic traditional construction methods. Typically, these systems are developed around specific modular or prefabricated components, which constrain the possible geometries and functionality of the resulting structure (Petersen, Nagpal, and Werfel 2011, Rubenstein, Cornejo, and Nagpal 2014, Lindsey, Mellinger, and Kumar 2012b). From a Design perspective, such efforts focus either on duplicating existing rectilinear forms as made by conventional construction methods or on local-to-global models which define sets of behavior in simulation and explore the resulting structures with little focus on physical constraints.

Single-node additive rapid fabrication (RF) and rapid manufacturing (RM) technologies have emerged, since the mid 1980s, as promising platforms for building construction automation. Whether liquid-based (*e.g.* stereolithography), powder-based (*e.g.* selective-laser sintering), or solid-based processes (*e.g.* fused deposition modeling), characteristic to such technologies are the following attributes: (1) the use of mostly non-structural materials with homogeneous properties; (2) the limitation of product size to gantry size; and (3) the layer-by-layer fabrication of products. A swarm approach to manufacturing can radically transform digital construction by: (1) digitally fabricating structural materials; (2) generating products and objects larger than their 'gantry size'; and (3) supporting non-layered construction by offering novel fabrication processes such as robotic weaving and free-form printing. These methods are conducive to function generation; however, they cannot be easily scaled to large systems. With swarm sensing and actuation, systems can become more responsive and adaptive to environmental conditions. Following Nature's way and an array of case studies, a swarm offers reliability and efficiency through distributed tasks, parallel actuation, and redundancy.

3.2 Tunability in Nature

(1). Spatial: In Nature, spatial material tunability is everywhere to be found in the biological world: from silk fibers providing tunability on the 15-micron scale (Zhao et al. 2005), to bone structures forming multi-cellular graded structures on the meso-scale (Carter 1984), to macro-scale branching trees, grading wood across scales (Plomion, Leprovost, and Stokes 2001).
(2). Temporal: Materials in Nature—specifically in the biological world—also change their properties over time—growing, adapting and repairing themselves. Further, temporal material transformation often comes with spatial transformation, with ever-changing variety in form (Robert and Friml 2009).
(3). Spatio-temporal: The natural world is filled with examples demonstrating spatio-temporal tunability—from the remodeling of spongy bone as it adapts to changing structural loads (Carter 1984) to trees and plants growing in accordance with environmental factors (Robert and Friml 2009). Living materials such as wood, skin, and bone offer true manifestations of both 'axes'—the spatial and the temporal—for grading material properties over space and time, and across their respective scales.

3.3 Tunability in Design

(1). Spatial: Research in Mediated Matter has focused on developing variable-property printing platforms delivered through a single node (Oxman 2010, Oxman 2011, Oxman, Keating, and Tsai 2011b). The variable property printing work has been investigated across multiple scales and properties in our group. Past work developed functionally graded concrete 3D printing that utilizes density gradients to reduce mass and improve structural capabilities. The completed work demonstrated material reductions of between 9-13% of the overall mass while maintaining the equivalent structural capacity of a fully dense member using radial density gradients in concrete bending samples. The work extended into large-scale 3D printing of architectural structures through a method termed 'Print-in-Place' construction, which was discussed in the background section of this PhD.
(2). Temporal: Product and architectural Design is limited in the ability to generate products with temporal tunability. Most temporal material tunability in Design relates to changing from one state to the other, much like a binary switch being able to shift continuously between two states. Multi-material additive manufacturing has led to some advances in this field, enabling complex 3D printed parts to react in the presence of water or alcohol to switch from one state to another (Tibbits et al. 2014). A very different approach to the same problem can be found in the Hygroscope (Menges and Reichert 2012) by Achim Menges and Steffen Reichert, which exemplifies a more direct transformation over time using a grown material—wood. Here thin sheets of wood, assembled in the right grain orientation, act as sensor, actuator and construction material simultaneously. As simple as it appears to be, it shows the sophistication in even the most common materials around us.

(3). Spatio-temporal: True spatio-temporal material tunability in digital Design and fabrication—where material can adapt and react to environmental stimuli through spatial material transformations over time—appears to exist only as a vision and lies beyond current technological abilities.

This research seeks to depart from these uniaxial fabrication methods and develop fabrication units capable of collaboration on a single task while simultaneously depositing tailorable, multifunctional materials. Further, I intend to demonstrate that my research framework is applicable across scales: from the micro-scale to the product scale and, uniquely, to the architectural scale.

3.4 Problem Definition

3.4.1 Spatio-temporal Tunability in Digital Fabrication

Digital Design and fabrication lacks the tools required to fabricate large-scale structures with high degrees of material tunability. Although significant advances have been made in multi-material additive manufacturing for higher degrees of material tunability, outputting meso-scale, spatially complex, multi-material products, the materials still perform poorly over time and are not applicable to large-scale architectural fabrication. Meanwhile, distributed robotic fabrication systems, have shown themselves to be highly communicative with a potential for large-scale fabrication, but the material strategies consist widely of prefabricated componentized assemblies with very little material tunability.

3.4.2 Problems

3.4.2.1 Material Tunability and Communication

Digital fabrication approaches can be classified with respect to two basic attributes: (1) the degree of material tailorability, and (2) the level of collaboration between fabrication units. Conventional manufacturing is typically confined to only one of these attribute axes; with certain approaches utilizing sophisticated tailorable materials (Oxman, Dikovsky, et al. 2014, Tibbits et al. 2014) but having virtually no communication abilities, and others assembling pre-fabricated building blocks with high levels of intercommunication between fabrication units (Gilpin, Knaian, and Rus 2010, Romanishin, Gilpin, and Rus 2013, Petersen, Nagpal, and Werfel 2011). A similar pattern is mirrored in biological systems: silkworms, for example, deposit a multifunctional tailorable material with minimal communication between organisms (Oxman, N., et al. 2014), while ants, bees and termites operate as multi-agent communicative entities assembling simple, unifunctional, 'generic' materials (Franks and Deneubourg 1997).

3.4.2.2 Large-Scale Digital Fabrication

Large-scale digital Design and fabrication is still largely governed by the relationship between machine-scale and product-scale. This results in architectural scale components being *produced in parts* (i.e. *assembled*), transported to the site, and put together—more often than not—by manual labor (Keating et al. 2014). Advances in robotic distributed fabrication for the large scale promise extraordinary potential, but have yet to be applied to structurally sound architectural embodiments.

The aim of this thesis is to explore these uniaxial manufacturing approaches and develop a novel, swarm-inspired distributed manufacturing method capable of fabricating tunable materials and—at the same time—holding true potential for the collaboration of fabrication nodes. This will enable large-scale fabrication by removing the gantry limitation and at the same time provide material tunability across scales within the resulting structure.

3.5 Aims & Goals

Developments in swarm construction have typically focused on the development of sophisticated communication and control protocols to support automated assemblies of basic, pre-shaped building components manipulated in pre-defined paths. In parallel, developments in additive manufacturing technologies have progressed towards printing multi-material assemblies with integrated functionalities. The technology proposed here seeks to unite swarm construction and additive manufacturing to create complex integrated building systems at micro, product and architectural scales. The aim is to demonstrate the true potential of this approach through the exploration of swarm fabrication techniques and case study projects.

My main goal is to enable automated digital construction and manufacturing using 'raw' materials rather than pre-shaped components. Developing a multi-robotic hardware platform, as well as working with actual biological swarms of various organisms (including ants and bees), I aim to illustrate the potential of two classes of fabrication—building swarms and guiding swarms—interfacing with their biological counterparts to respond to external environmental stimuli. Work described in this thesis aims to develop a new theory of digital manufacturing that unifies swarm construction and additive manufacturing, the biological world and the digital, in design and fabrication.

Biological case studies and experiments associated with them generate a theoretical foundation and experimental platform towards swarm design that is one or all of the following: 1) large in scale; (2) able to generate structural materials with variable properties; and (3) sustainable (i.e. does not rely on its own energy resources and can potentially use natural resources). Work described in this thesis also aims to develop a scientific and engineering base of knowledge on printable materials, additive manufacturing strategies, swarm intelligence and modeling tools for this sort of technology, referred to as swarm design.

Two defining axes for swarm printing include communication, interactivity and programming (X) and material integration sophistication given by integrated functionality (Y). Silkworms generate highly tailorable materials with limited communication between worms, while termites assemble primitive aggregates using sophisticated social communication. The research aims to develop the first steps towards a swarm design paradigm uniting the two.(Oxman, Duro - Royo, et al. 2014)

(1) Materials: A suite of materials processes. The emphasis will be on materials that can be characterized as having (a) tunable properties such as elastic moduli, (b) environmentally benign and biologically compatible properties, and possibly (c) the ability to respond to the environment.
(2) Fabrication: Fabrication strategies matched to materials, and able to meet property, organization, resolution, and cost requirements for realistic applications. The complex nature of the products demand fabrication approaches that differ from those used in the established product Design and building industry.
(3) Robotics and computation: Hardware tools and control software for swarm printing at the material, product and systems levels. This research will also produce physical constructs, testing and demonstrating the merit of fabrication hardware developed, constructed materials, taking into consideration structural as well as environmental properties of the produced object and architectural structures.

The three research areas above combine basic design studies with intensive engineering efforts, to set the foundational knowledge towards a practical technology of swarm printing, which will be demonstrated through the deployment of a novel robotic system for the architectural scale.

Successful results will demonstrate a foundation for a new design and fabrication approaches with high impact implications for the designed and built environment. Biological swarm construction offers the benefit of integrating material processing and assembly within a single process. Significant improvements in cost, complexity of product, and robustness of production are hinted at by looking at biological materials such as silk. This research offers the potential for opening purely artificial robotic processes towards biological processes not only by mimicking them, but also employing them as part of the Design and fabrication process.

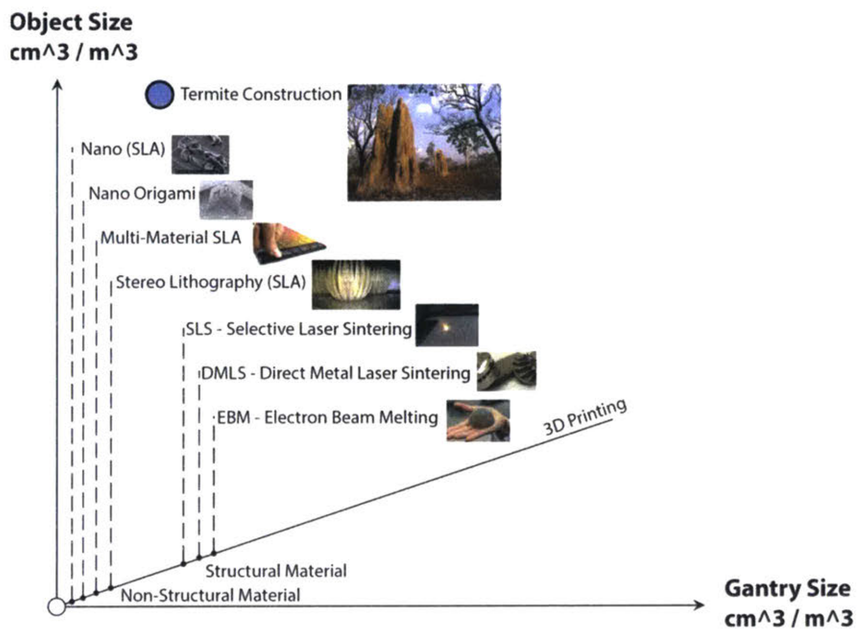

Figure 3.1: A 3D Swarm printing paradigm uniting Design, engineering, and digital manufacturing emerges beyond a certain product and gantry size, overcoming the size, communication and material functionality limitations of traditional digital fabrication and manufacturing technologies. Mediated Matter Group, MIT Media Lab.

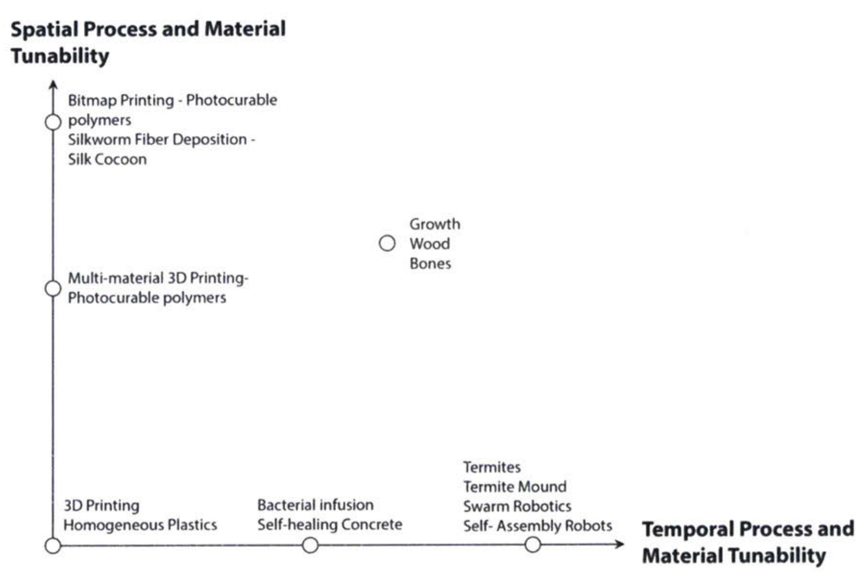

Figure 3.2: Material processes tailorability in Nature and digital fabrication (3D Printing). Mediated Matter Group, MIT Media Lab.

Chapter 4

Material Tunability Processes
Experiments in Material Deposition and Variable Material Output

4.1 Introduction

When considering design approaches, the material and material manipulation processes play a pivotal role. The transition from traditional Design to CAD-based Design brought about new freedoms in form generation. Digital fabrication tools and CAD/CAM software also widened the scope for what is feasible for three-dimensional material outputs, just as the automation of previously manual processes and the addition of techniques such as 3D printing opened the way for a more comprehensive design and fabrication exploration towards the automation of larger-scale constructs and graded/variable property material deposition across scales.

In the following, I will try to make a case for the imminent need of pure material deposition experimentation by describing various experiments and tools leading up to distributed fabrication ideas for the larger scale. I will discuss case study projects that are related, but not yet scalable, and which potentially enabling larger-scale construction made possible by the development of and research into new forms of automated material deposition tools.

To bring this to the architectural scale, of course, we need varying functionalities, such as transparency in the quality of glass and structure in the quality of stone and steel. How do we transition from homogeneous polymer 3D printing to more sophisticated materials? This question is as old as 3D printing, invented over 50 years ago, and we are still trying to close the gap between the geometrically complex constructs achievable today (Bader et al. 2016) and the mostly basic material composition and quality of the very same constructs.

Experimental material processes will be discussed, which on one hand aim to expand the material palette of additive manufacturing, and on the other hand can tackle the scaling problem to at least some degree, leading towards ideas of distributed material fabrication systems in this thesis.

The following chapter presents previously published work, specifically the papers 'Robotically Controlled Fiber-based Manufacturing as Case Study for Biomimetic Digital Fabrication' (Oxman, Kayser, et al. 2013), 'Freeform 3D Printing: Towards a Sustainable Approach to Additive Manufacturing' (Oxman, Laucks, Kayser, et al. 2013), 'Modelling Behavior for Distributed Additive Manufacturing' (Royo et al. 2015), and 'Additive Manufacturing of Optically Transparent Glass' (Klein et al. 2015). Each of these digital fabrication and material experiments represents a single step towards either higher degrees of material tunability in digital fabrication and design and/or aiming to reach a larger scale through the digital material processes developed. Early attempts at working with fiber/matrix-based materials are discussed. These experiments were the results of the initial studies of the material silk, the silk cocoon structure and its compiler the silkworm. These studies of a biological material system are explored through attempts of mimicry and scaling of the material system by synthetic materials and digital machines, which later led to the Silk Pavilion, discussed later in Chapter

6.
The cable-suspended robotic fabrication system presented in this chapter is showing early steps towards a larger fabrication paradigm where the machine is specifically designed to parasitically attach to its environment and thus could potentially reach very large scales depending on the surroundings. Here, already four machines work together (at least in simulation) in order to reach an even larger working envelope and thus introducing ideas of multi-robotic fabrication nodes in previous work.
And lastly, glass 3D printing will be introduced as a new process, demonstrating transparency and inertness as new and valuable material properties for the architectural scale of 3D printable materials.

4.2 New Tools for Variable Material Deposition

4.2.1 Nature Inspired Fiber-based Robotic Fabrication

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, Keating, and Tsai 2011a). Additive manufacturing platforms like 3D 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, Tsai, and Firstenberg 2012).

Figure 4.1: *Bombyx mori* silkworms in petri dish, feeding of mulberry chow.

Furthermore, construction processes found in the animal kingdom, such as woven spider webs or aggregate bird's nests, are characterized by the animal's ability to generate, distribute, orient, dandify and assemble fiber-based materials (Benyus 2002, Hansell 2005). As a result, biological structures (including animal architectures) are considered highly sustainable natural constructions. 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. 2010).

Figure 2.36: 25X magnification overview SEM micrograph of a domesticated *Bombyx mori* cocoon, Image by Dr. James Weaver from the WYSS Institute, Harvard Univeristy.

In this section of this chapter, a suite of analytical protocols is reviewed, designed to examine the silkworm's process of constructing a silk cocoon. We then demonstrate a set of design tools created to reconstruct the cocoon in various length-scales using a 6-axis KUKA robotic arm.

4.2.1.1 Introducing the Silkworm *Bombyx mori*

Silk is one of the most ancient, expensive, and highly valued materials in the world. It has many applications in textiles, medicine, and industry (Omenetto and Kaplan 2010). The domesticated silkworm *Bombyx mori* constructs its cocoon using composite fibrous material made of fiber (fibroin) and matrix (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 that it can triangulate and attach its fibers parasitically to its immediate environment. While spinning this scaffolding, it will close in on 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).

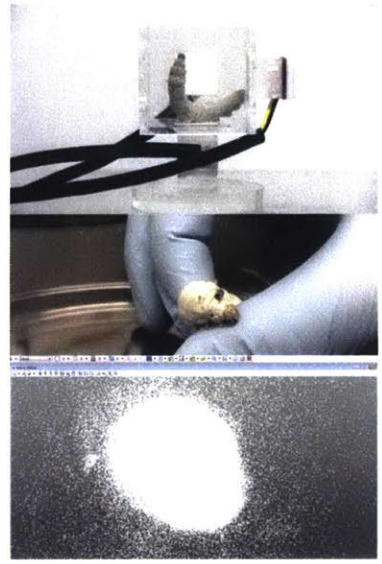

Figure 4.2: Silkworm motion tracking rig (top), Silkworm with magnet (middle), resulting point cloud in Generative Components software (in collaboration with Carlos Uribe Gonzales).

4.2.1.2 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 that would be 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.

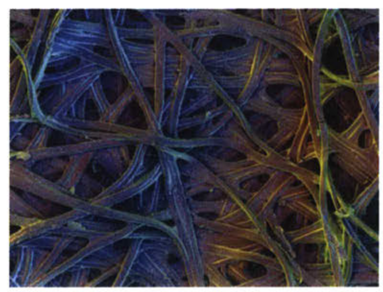

Figure 4.3: 300X magnification polychromatic SEM micrograph of external surface, domesticated Bombyx mori cocoon. Image: James Weaver, WYSS Institute, Harvard University.

An experimental sensor rig measuring 40 mm X 40 mm X 40 mm was developed using magnetometer sensors placed on 3 planes of the cube. This allowed for data capturing from a 1 mm X 2 mm magnet attached to the silkworm's head (Figure 4.2). After the magnet was attached, the silkworm was placed within the described space. As expected, the silkworm attached its fiber scaffolding 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 4.2.

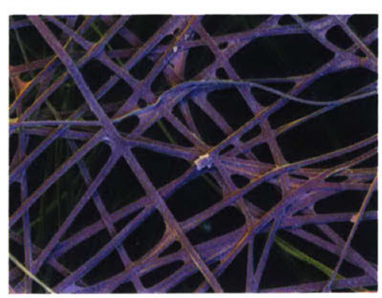

Figure 4.4: 2300X magnification polychromatic SEM micrograph of the silk support scaffold of a domesticated Bombex mori cocoon. Image: James Weaver, WY WYSS Institute, Harvard University.

4.2.1.3 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 of converting 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.

4.2.1.4 SEM Imaging across Multiple Scales

In order to investigate local fiber placement of the cocoon and gain a better understanding of the scaffolding structure, SEM images were taken of the outer layer of the cocoon, equatorially bisected sections, and internal layers of the *Bombyx mori* cocoon.

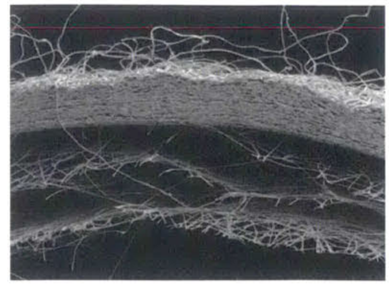

Figure 4.5: 230X magnification plan view SEM micrograph of an equatorially bisected domesticated *Bombyx mori* cocoon. Image: James Weaver, WYSS Institute, Harvard University.

4.2.1.5 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 silkworm's 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 silkworm's 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 silkworm's cocoon construction process: (a) parasitic construction and (b) cocoon spinning.

Figure 4.6: Initial small scale test free-form printing using a Makerbot Stepstruder. Previously published in (Oxman, Laucks, Kayser, et al. 2013)

4.2.2 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 (Figures 4.9 and 4.10). 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. Figure 4.13 compares the biological extrusion process using silk and its digital-fabrication counterpart using composite HDPE.

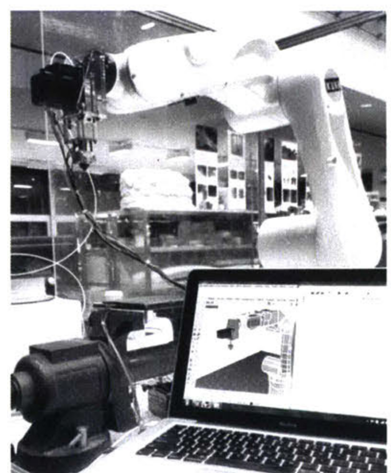

Figure 4.7: Stepstruder attached to the Kuka robotic arm, simulating toolpath. Previously published in (Oxman, Laucks, Kayser, et al. 2013)

4.2.2.1 Extruder Tool Development

Preliminary tests explored the use of a Stepstruder[1] tool-head with Acrylonitrile Butadiene Styrene (ABS) filaments to test the concept of drawing a fluid plastic material through space (Figures 4.6 and 4.7). As

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[1] MakerBot, Stepstruder MK7

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 (Figure 4.8).

Figure 4.8: Extruder body, fabricated on the laithe from aluminum stock.

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[2]. 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 stepper motor[3]. A step driver[4] controls the motor turning the gear fixed to the auger bit. When the gears turn the auger bit, a steady supply of plastic pellets is fed from a hopper through flexible tubing via a Venturi air-powered vacuum conveyor for material advancement. As the pellets are transferred down through the housing, the heater cartridges heat the pellets to about 130°C as regulated by an Arduino-controlled thermistor, while the downward pressure advances the molten material out through the selected tip.

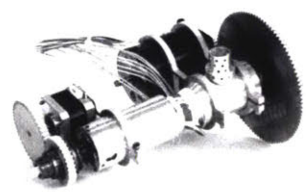

Figure 4.9: High Density Poly Ethelene (HDPE) pellet extruder with variable nozzle dimater/shape. Previously published in (Oxman, Laucks, Kayser, et al. 2013)

Figure 4.10: Multistrand extrusion upwards in free-space. Previously published in (Oxman, Laucks, Kayser, et al. 2013)

4.2.2.2 Material Tests

For the proof-of-principle experiments, we chose high-density polyethylene (HDPE), commonly used 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° C allowed us to melt, extrude, and harden it in the air using a compact setup that is easily mountable on the robotic arm.

A variety of extrusion nozzle designs were explored and developed based on material properties and deposition processing constraints. The initial nozzle was developed as a variable diameter and cross

2 12V 40W Ceramic Cartridge Heating Element

3 Oriental Motors, Nema 23 Stepper Motor

4 Gecko, G201X Digital Step Driver

section tip (Figure 4.9). With an additional stepper motor mounted near the bottom of the extruder this nozzle is able to vary between a 10 mm round extrusion to an 8 mm triangulated extrusion profile.

Following initial experiments with the variable nozzle, a series of interchangeable nozzles were developed, including two tapered single-diameter extrusion nozzles of different length. The diameter of these single extrusion tips consisted of a 3 mm extrusion hole resulting in a 3.5 mm final extrusion.

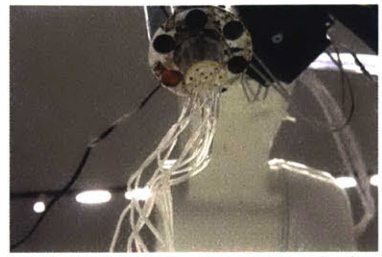

Figure 4.11: Close up view of the multi-strand extrusion nozzle while printing.

Additional nozzles were developed to enable more complex extrusion profiles. For example, one of the nozzles 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 3.5 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 nozzle and a cylinder shaped interior wall. Advanced versions of this nozzle incorporated a multi-strand approach. Two multi-strand nozzles were developed, one with a variety of self-similar holes and another with varying holes. The holes of the second nozzle 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 (Figure 4.11).

Figure 4.12: Active 360 air cooling of the nozzle area.

4.2.2.3 Discussion on Material Extrusion Tests

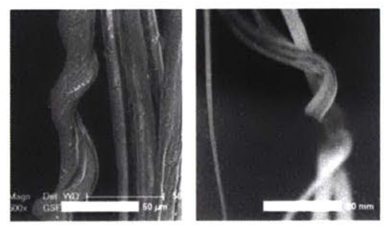

Figure 4.13: Comparison across scales, left: SEM of silk fibers, right: close up view of self-alignment in the HDPE extrusion. Previously published in (Oxman, Laucks, Kayser, et al. 2013)

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 local support (as the structure progresses in vertical space) and self-alignment due to the forces of gravity. 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 and Noriega 2001). Figure 4.13 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.

Figure 4.14: Extrusion testing re-attachment to previously cooled areas repeatetly in order to create larger constructs.

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 stands, which retain more heat and allow for better reconnection to existing cooled extrusions (Figure 4.15 and 4.16).

Figure 4.15: Construct printed with the multi strand extrusion approach approx. 40cm x 30cm in size.

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.

4.2.2.4 Free-Form 3D Printing Conclusion

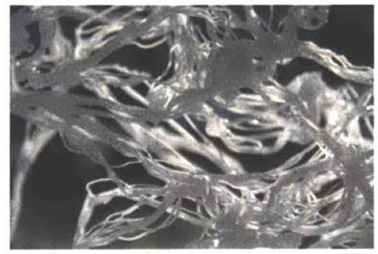

Figure 4.16: Close up view of reconnecting strands of multistrannd free form printing.

The Free-Form Printing tool and related experiments presented here focus on the intersection of biologically inspired design, fibrous construction and tunable mono-material construction research. Applications for this novel process may be 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 paper provide proof-of-concept for Free-Form 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. However, most importantly these experiments may guide us on the way towards larger-scale printed constructs as well as tunable material properties on the fly, as some experiments suggest the possibility of varying extrusion diameter as well as multi-strand extrusion on the fly, thus widening the scope for more adaptability during the fabrication process.

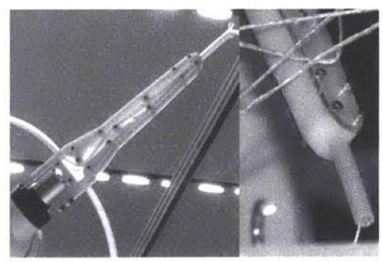

Figure 4.17: Fiber pulling (and wetting) tool end effector. Previously published in (Oxman, Kayser, et al. 2013)

Here, gravity, as well as the cooling and shrinking of the individual strands of HDPE, is controlling the local variation—the self-alignment—of the individual strands controlled globally by a digital path trajectory of the robot.

Figure 4.18: Fiber pulling tool on robotic arm, wooden scaffold structure with hooks. Previously published in (Oxman, Kayser, et al. 2013)

Based on the mono-material synthesis approach using the thermoplastic extrusion method, further experimental synthesis approaches were developed and simulated, and are described in the following sections.

4.2.2.5 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 figure-8 pattern, building up wall thickness for the cocoon over time by constantly reconnecting the fibers locally inside the previously built scaffolding.

4.2.3 Synthesis 3: Parasitical Attachment and Fiber Pulling

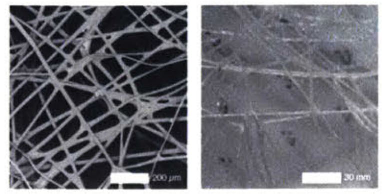

Figure 4.19: Comparion across scales, left: SEM of silk scaffolding structure, right: solidified fiber resin composite lattice. Previously published in (Oxman, Kayser, et al. 2013)

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 4.19, 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. For the synthesis of this process we developed a rig to which the robot can attach fiber whilst pulling the fiber through a resin bath right at the tool head, not unlike the biological process.

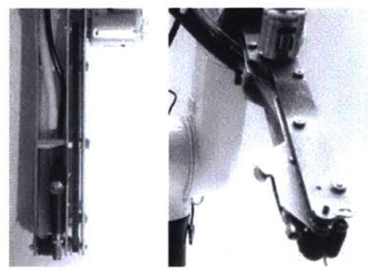

Figure 4.20: Fast thread deposition tool. Previously published in (Oxman, Kayser, et al. 2013)

4.2.4 Synthesis 4: Fast Deposition Tool

Figure 4.21: Fast thread deposition test of fibers on square metal grid to test vertical adherance.

A secondary end-arm tooling was developed, which deposits fiber at 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 for the fiber 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 4.20 and 4.21) 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.

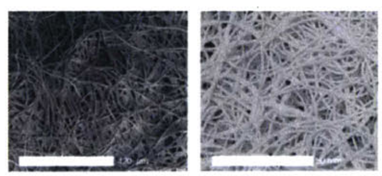

Figure 4.22: Comparison across scales, left: SEM of outer silk cocoon surface, right: fast deposition non-woven material. Previously published in (Oxman, Kayser, et al. 2013)

The experiments demonstrate that an external structure (equipped here with hooks) is required in order for the robotic tool to "print" with fibers. These developed processes demonstrate that it is possible to create fiber-based rigid structures, which may be used for 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. In fact, since these early experiments were done in 2012, researchers at the University of Stuttgart have achieved large-scale pavilion structures using methods similar to those presented here, as discussed in this background chapter of this thesis.

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. The process of data collected from the biological world combined with experiments into novel fiber placement methods could lead to integrative and sustainable fiber-based manufacturing using Nature as inspiration and technological advances as facilitators.

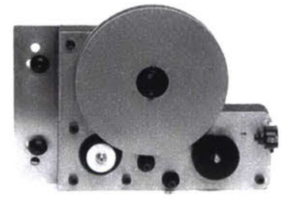

Figure 4.23: Cable-suspended robotic unit (of four per robot). Previously published in (Royo et al. 2015)

4.3 New Machines for Material Deposition

4.3.1 Cable-Suspended Robotic Construction System

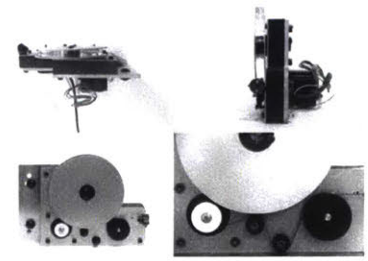

Figure 4.24: Cable-suspended robot single unit from varying views. Previously published in (Royo et al. 2015)

In the previously discussed examples of experiments and material tunable fabrication, the technology was largely predefined, as in the positioning platform using a robotic arm, where only new end-effector tools for such a system were explored. In this case study project, the positioning technology is at the core, parasitically attaching to the existing environment as a whole deposition machine.

The Cable-Suspended Robotic Construction System was developed as a scalable approach for large-scale construction. A single cable-suspended robot consists of four units, each pulling and releasing a cable at precise increments. Each cable culminates into a single node at which the fabrication end effector hangs. At each unit, the cable is wound around a spool. Each spool is motorized and has feedback control on cable length.

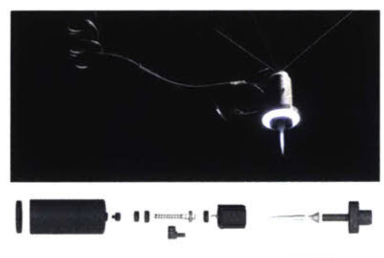

Figure 4.25: Extruder hanging from the four cable units with coiled material feed system to the left. Previously published in (Royo et al. 2015)

Machine control firmware was developed in C and C++ language (developed by Jorge Duro Royo and not discussed here in detail) using micro controller boards[5]. The boards distribute serial signals to stepper motors[6] via the stepper motor drivers[7]. The stepper motors are NEMA 23 in size and are rated for a holding torque of 2.83 newton-meters. The drivers permit a maximum current of 7.8A and are powered separately from the electronic controls with a 48V power supply. Constant force spring motor assemblies[8] are used to spool up excess cable as well to keep tension on the pulleys. The micro controller receives feedback data from incremental rotary encoders[9] and custom-made zero switches made up of a copper contact and a connecting copper element attached to the cable at the right length. Each agent is suspended via four straight center stainless steel cables which are encased in a helically

[5] Arduino Mega 2560

[6] Gecko 6723-400-4

[7] Probotix Bi-polar 7.8A

[8] Stock Drive Products/Sterling Instruments, ML 2918

[9] Yumo, A6B2-CWZ3E-1024, 1024 P/R Quadrature

wound nylon/polyurethane sleeve[10]. The custom-built extrusion head assembly is composed of a stepper motor driving an extrusion screw inside a nylon barrel with a material inlet to the side and rubber seals separating the extrusion material from the stepper motor drive around the shaft. Lead weights are applied for stabilization of the extruder head; cable fixtures are attached to four incoming cables with a machined plastic housing and a material supply inlet (Figure 4.25). The material feed for the extrusion end effector is composed of a pressure pot containing paste-like (in the experiments a lightweight gypsum plaster mixture) material fed to the extrusion heads by narrowing the flexible tubing diameter towards the extrusion head.

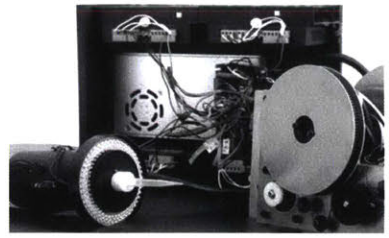

Figure 4.26: Cable-suspended system, from left to right: extruder, four stepper motor drivers and power supply and a suspension unit. Previously published in (Royo et al. 2015)

This cable suspended extrusion system is a very interesting contender for large-scale fabrication as in a urban setting it could attach to any surrounding buildings creating a very large work volume to machine size. As described previously, a single node consists of a small number of parts in a compact assembly; only the length of string, and size of the spool and motor would limit the printing envelope. Although the material supply also has to be considered as a limiting factor, one can imagine a tubular material feed system that would not interfere with the positioning cables. Again, in an urban environment the material may even be gravity-fed to the extrusion head. The dream scale for this system would be skyscraper scale, where it could attach parasitically to buildings and construct in the voids between them.

Figure 4.27: First experiments with glass extrusion at the MIT Glass Lab. Pouring glass into a crucable with an opening at the bottom. Image John Klein, Mediated Matter.

4.3.2 Transparent Glass 3D Printing for the Large Scale

When Mike, John, Peter, Shreya and I started this project, we were dreaming of the moon and beyond. Since my experiments in solar printing Lunar and Martian regolith simulants in the Moroccan desert in 2012, I had hoped for another opportunity to try out these ideas in a more controlled environment. However, since we had limited time and budget, we started with soda lime glass which was commonly used in the Glass Lab at MIT. This journey began (at least in our minds) in outer space and landed us at creating the first optically transparent glass 3D printer, quite in contrast to the deep black molten regolith samples made in the desert. Instead of producing with sunlight, it became about the optical qualities of glass and light, still driving this project today into the architectural realm. In the following I will describe the glass printer's basic setup and functionalities, leading to a discussion of how this process may be used as a digitally fabricated template for growth and energy production on the architectural scale.

Figure 4.28: Glass 3D Printer V1 in the Media Lab lobby. Image: Chikara Inamura, Mediated Matter.

The glass 3D printer is a fully functional digitally driven material extrusion system for optically transparent glass. The 3D printer consists of scalable modular elements able to operate at the high temperatures required to process glass from a molten state to an annealed product. This process enables the construction of 3D parts as described by computer-aided design models. Processing parameters such as

[10] Stock Drive Products/Sterling Instruments, Synchromesh, 1.6 mm outer diam.

temperature, which control glass viscosity, and flow rate, layer height, and feed rate can thus be adjusted to tailor printing to the desired component, its shape, and its properties. Printed parts demonstrated strong adhesion between layers and satisfying optical clarity.

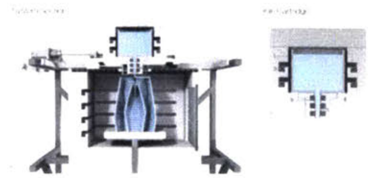

Figure 4.29: Rendered cross-section of the system showing (A) the printer during fabrication, (B) the Kiln Cartridge C) the Crucible Kiln and (D) the Nozzle Kiln. Previously published in (Klein et al. 2015)

Initial tests were conducted using a previously heated ceramic crucible; molten glass was added and a slow flow was observed through the hole at the base. The tests proved that a gravity-driven feed was feasible, but suggested that heating of the feed material would be critical. The second step involved the addition of a kiln surrounding the crucible during the process; glass flow of continually heated feed material was demonstrated. Flow was continuous and the glass was allowed to coil autonomously, forming tapered cylindrical shapes.

Computer control of the Z axis was then implemented, which enabled the system to maintain constant deposition height and to produce coiled cylinders with constant diameters. To create the first designed shape, bumpers were mounted on the frame and the crucible kiln was manually moved, successfully producing a square cross-sectional object. Digital control on the X and Y axes was then added, and more complex shapes were successfully fabricated. Implementation of software and motion control also provided the chance to set a constant travel speed. A rectangular prism being printed with this setup is presented in Figure 4.30 (A).

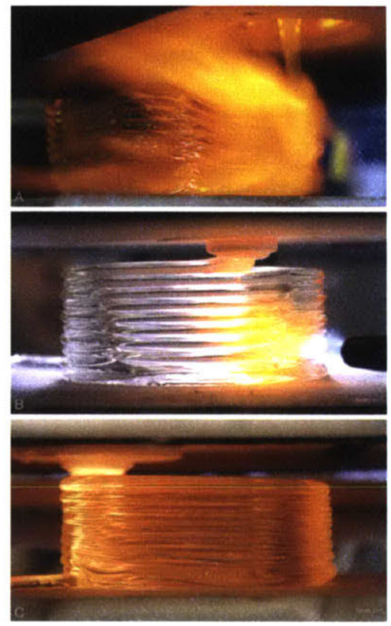

Figure 4.30: Evolution of the printing process from its early stages (A), through the introduction of a nozzle (B) to the current setup with an annealing chamber (C). Previously published in (Klein et al. 2015)

Despite the motion system reaching satisfactory mechanical control and precision, the printed parts showed inconsistent filament diameter, poor adhesion between layers, and rapid accumulation of defects. These problems derived from a common cause: the fact that glass was dripped from an offset height. An independently heated ceramic nozzle to be attached to the crucible was therefore designed and produced; with the nozzle tip below the carriage level, it was possible to print with no offset height. With this upgrade, control of the layer height was achieved and the above-mentioned issues were overcome. A cylinder being printed after the addition of the nozzle is shown in Figure 4.30 (C).

Products produced in this early development of the system are shown in Figure 4.31 (B). The 3D-printed glass objects described here can be extended to implementations across scales and functional domains including product and architectural design. The light patterns that can be created using this process may not only be visually interesting but may be transformed into function in guiding light.

The glass 3D printer provides opportunities in templating the growth and cultivation of microorganisms such as Cyanobacteria on the architectural scale. Since the first demonstration of the glass printer, further advances have been made by the Mediated Matter group in producing larger scale components, which can be assembled into 3-meter-tall columns, and further research is planned, truly bringing it into the architectural realm via a façade system. Glass provides an inert environment for bacterial growth, which could be used to embed living organisms directly into the walls and windows of our buildings, thus converting sunlight energy into fuel and potentially heating and cooling a building. In a 3D printing approach, these walls can be optimized for sunlight exposure at any given location and internal spatial features can potentially be designed to guide the microorganisms, creating channeled networks for pumping liquid media through. These new potential capabilities arise out of simply adding a new (yet old) material to the catalogue of 3D printable materials and thus underline the need for material experimentation in the domain of additive manufacturing and digital fabrication as a whole.

Whether fiber-based digital fabrication, cable suspended robots or glass 3D printing, these experiments in digitally controlled materiality may open the doors to novel forms and functionalities in the built environment.

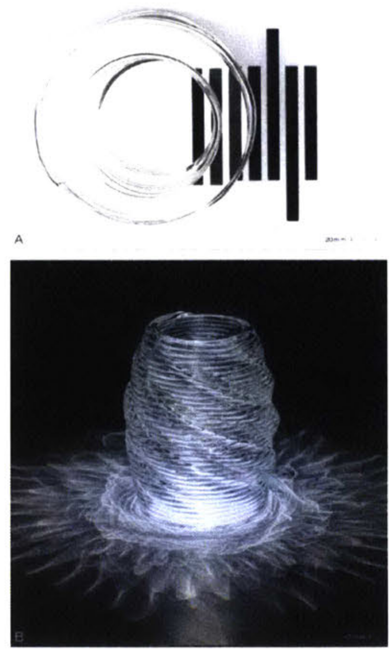

Figure 4.31: Optical properties and caustic patterns of printed parts. (A) Top view of a 70mm tall cylinder showing a high level of transparency; (B) caustic patterns created by illumination from a suspended overhead LED. Previously published in (Klein et al. 2015)

Chapter 5

Research Framework
Theories of Templating and Augmentation

5.1 Introduction

Two strategies are put forward for enabling material tunability through a biological or robotic agent-based fabrication system. The first strategy is termed *templating*, and involves a mapping process for top-down guidance of fabrication nodes. The second is termed *augmentation,* and involves a functional enhancement of the fabrication nodes for bottom-up control. These two strategies form the basis for the theoretical research framework (Figure 5.1), using templating and augmentation of either *biological* distributed systems or *technological* distributed systems, where Nature can act as the input, the output or the compiler. Four research thrusts are presented, which lay out the interaction between the technological and the biological, one informing the other via templating or augmentation. The aim of this framework is to give structure to the experiments with insects and robotics and clarify the relationships between Nature and technology for this research, with the aim of enabling higher degrees of material tunability in digital fabrication and Design across scales.

5.2 Templating and Augmentation

Templating can be defined as a top-down tensor field applied to either a biological distributed system via technology, or a robotic distributed system via biology. For example, ants can be guided by light, changing their fabrication strategy behaviorally, while a robotic swarm could use the logic or rules found in a biological distributed system such as birds' flocking behavior.

Templating Nature has a long history, mainly in controlling the growth of plants and trees. The tradition of guiding tree roots to form bridges by the indigenous Khasi tribes of Meghalaya in the Northeastern Indian Himalayas serves as a great example of templating a living organism, the *Ficus elastica*, by guiding its growth to form a bridge over the course of 15-30 years (Shankar 2015). Artists have also guided the forms of trees to create living garden furniture, and a company has even been formed around the guided growth of willow trees to 'build' furniture in a sort of outdoor factory (Full-Grown-Company 2017). So by no means is the templating of organisms new in the sense of trees and plants, as their growth can be easily manipulated by jigs or even light, as seen in tropism in plant growth. The previously discussed examples of templating bees to create a wax vase, caddis fly larvae to make jewelry, or controlling the growth of crystals spatially, also present valuable insights into how a biological or chemical compiler can be used and guided by spatial constraints only.

However, none of these examples have used any digital means to facilitate templating of the organisms, instead requiring many hours of manual labor to guide these living structures into a desired product output. In this framework, I am working towards the potential of digitizing some of these principles as well as expanding these basic ideas foor how multiple organisms working together as a distributed fabrication system can be tested and implemented.

Augmentation is defined as a more direct intervention in biology or technology, where behavior is guided more from the bottom up through a constant feedback loop. For example, a non-communicative organism could be augmented by inducing distributed logic from a naturally communicative insect, via a combination of external distribution tracking over a surface and a thermal gradient map guiding the distribution of the organism over the same surface, thus embedding or augmenting a new set of rules onto an organism run computationally.

Templating may be described as static form of alteration and augmentation a more dynamic way to facilitate a product outcome. The following diagram shows the interconnected fields and strategies for the four research thrust in this design framework, which will be discussed in the next section.

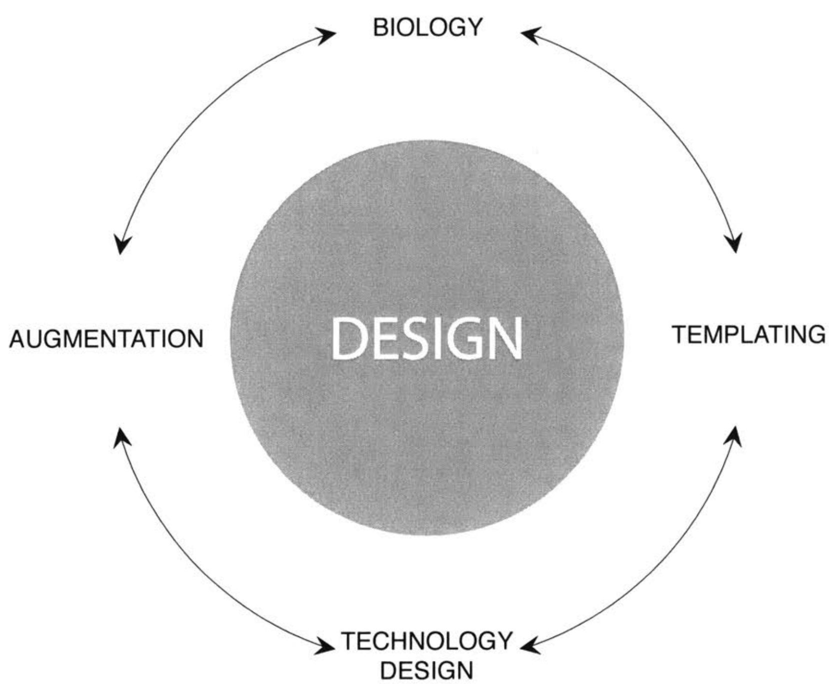

Figure 5.1: Left: Diagram showing the interconnected fields and strategies for the four Research Thrust in this Design Framework. Templating and Augmentation are used as strategies to tighten the relationship between Biology and Technology for Digital Fabrication.

5.3 Research Thrusts

5.3.1 Biological Templating for Design

The first research thrust involves the templating of a biological fabrication system, for example, by guiding it via a physical template/superstructure or non-physical stimuli such as a gradient of temperature, light or humidity, to produce a predestined Design outcome. This approach—to *guide* a biological fabrication system—can be placed in the order of top-down control in respect to a global product outcome. However—on local scales—it does not provide precise control strategies, as fabrication strategies inherent in an organismic system may not be altered but rather are chosen and regarded as useful givens for the fabrication process.

5.3.2 Technological Templating for Biology

The second research thrust involves the technological mapping and modification of an environment or some conditions of an environment to alter the behavior of a biological system, not through preventing alternatives for fabrication output from the top down, but instead providing new alternatives through the new environment. This approach may enable behavioral modification as well as changing the fabrication output through a technologically templated environment without direct physical interaction between template and organism, but rather through conditioned environmental parameters.

5.3.3 Biological Augmentation for Design

The third research thrust is comprised of a functional enhancement for Design via a biological intervention. In this approach, an organism may be augmented by the introduction of a new set of rules not previously inherent in the species, thus changing the fabrication output either formally in terms of geometry and/or physically via material modification. While templating may be categorized as a *static* form of spatial environmental manipulation, biological augmentation needs to be dynamic, able to adjust parameters over time as through a feedback loop, including the monitoring of Design output and biological fabrication system for constant adjustment of the dynamic embedded or environmental parameters.

5.3.4 Technological Augmentation for Biology

The fourth research thrust consists of a technological functional enhancement for a biological system. An organism may be augmented via invasive implants tapping into existing sensing capabilities and/or the introduction of new ones to steer locomotion, material deposition and potentially the material itself. In future research the material of an organism and its behavior may be genetically modified for direct and designed product output of an organismic fabrication system. This final approach can merge the biological with the technological for a fabrication output, being a truly bottom-up approach to digital fabrication. The final Design and fabrication output springs from the embedded Design strategies inherent to the designed system, and not from a predestined desired product outcome given to the techno-organismic system. Functional requirements and properties, rather than shapes, are defined for a product outcome.

5.4 Conclusion

The research framework described above guides and informs all experimental case studies in distributed fabrication. While the two strategies of templating and augmentation with the four research thrusts create the foundational pillars for this research, the three modalities of energy, matter and organism, or input, output and compiler, enter the research in different capacities and forms and are sometimes only present individually in practice. While, not all criteria of this research framework can be met in practice due to time and technological limitations, this framework does not only serve my PhD research but also provides room for exploration far and beyond.

Chapter 6

Research Framework in Practice
Design Applications of Templating and Augmentation

6.1 Introduction

The research framework is put into practice through several research projects (case studies). In my applied research, specifically, silkworms, ants and bees have been studied for their distributed Design and fabrication capabilities. Technological intervention via templating and/or augmentation through robotic light templating of ants, spatial and thermal gradient augmentation of silkworms, and environmental templating of bees have been studied and tested in experiments.

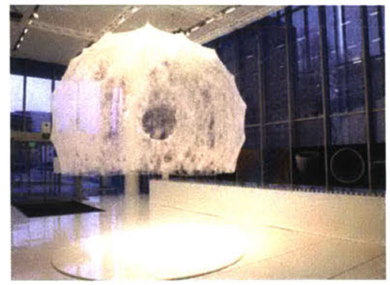

Figure 6.1: Final Silk Pavilion in the MIT Media Lab lobby. Image: Steven Keating, Mediated Matter.

6.2 Research Thrusts in Practice

6.2.1 Biological Templating for Design: Silk Pavilion as Case Study

Figure 6.2: Silk worm deposting silk on the CNC scaffolding structure (template). Image: Steven Keating, Mediated Matter.

The Silk Pavilion explores the relationship between digital and biological fiber-based fabrication on an architectural scale.

Its primary structure comprises 26 silk-threaded polygonal panels laid down by a CNC (computerized numerical control) machine. Inspired by the silkworm's 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. 6500 silkworms were positioned on the scaffold, spinning flat non-woven silk patches to locally reinforce the CNC-deposited silk structure (Figure 6.1).

Figure 6.3: CNC end effector fiber deposition tool.

In the Silk Pavilion project, numerous experiments on live *Bombyx mori* silkworms were developed to alter and manipulate silkworms' spinning behavior in order to develop digital methods to guide the silkworm distribution and material application on a large-scale scaffolding superstructure.

Figure 6.4: CNC deposited silk thread template.

Following previous experiments in fiber material deposition, discussed in Chapter 4, another fiber deposition tool was developed for this project in order to create a template for silkworms to fabricate upon. A fiber deposition end effector tool for a large CNC router[11] was developed in order to fabricate large CNC-fabricated non-woven fiber panels. As shown in Figure 6.3, this tool consists of a turned aluminum shaft with a fiber inlet on the side. At the bottom of the shaft sits a press-fit ball bearing, which holds a 2 mm stainless steel tube. This tube is separated into two pieces in the middle and held together by a tightly wound spring that acts as a tension release during fabrication. Aluminum frames were developed and fabricated using a water jet cutter in order to fabricate large-scale panels to be assembled to a

[11] ShopBot, PRSalpha 120-60

large-scale structure as demonstrated in Figure 6.6.

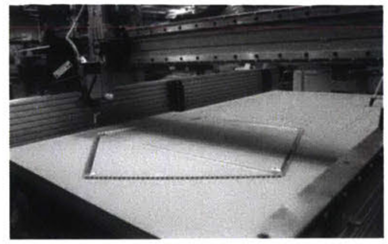

Figure 6.5: CNC fiber deposition on temprary aluminum frame.

Figure 6.6: Assembled temporary aluminum frames.

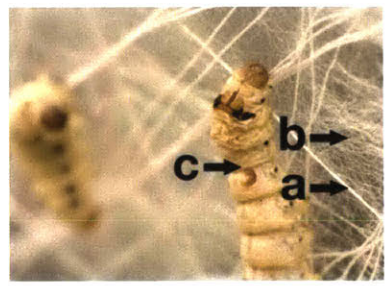

Figure 6.7: Templated Swarm. Silkworms *Bombyx mori* co-spin on CNC fabricated silk scaffolding structure. a) 0.4 mm diameter silk thread, b) silk deposited by silkworms on scaffolding, c) silkworm *Bombyx mori*.

Silkworms do not have social hierarchical system structures like those found in termite colonies, but are extremely adaptable to spatial parameters and environmental factors in their immediate environment. By studying their spinning behavior and determining necessary spatial constraints to control it, we were able to demonstrate that collective multiple silkworm spinning is a viable method to creating a fibrous 3D membrane. We altered the silkworms' spinning behavior—from naturally spinning a cocoon—to spinning a flat silk 'patch' on a template. In this proof-of-concept experiment, a silkworm swarm was controlled by spatial constraints via a digitally (CNC) constructed superstructure using a custom computational algorithm that takes into account the spatial parameters established in earlier experiments. Using basic rules such as the silkworm's spinning reach and anatomy, we demonstrated initial steps towards a digitally controlled system by creating a large-scale (12 ft x 12 ft) pavilion using a biological swarm. Here, the global Design was controlled and constructed digitally (templated) and the biological swarm of silkworms created variations in density and distribution locally. The superstructure was made from 15,132 meters of silk thread, while the silkworm 'swarm' deposited approximately 6,500,000 meters of silk fiber creating a highly complex micro structural membrane. The task of generating a 3D path for digital fabrication of a thread 6,500,000 meters in length would be formidable; in the case of the Silk Pavilion, however, this is accomplished by generating only the global scaffold strategy and leaving the local control and micro-structural fabrication to silkworms controlled through external factors such as geometry, light and temperature.

The global Design of the pavilion was derived from desired light effects informing variations in material organization across the surface area of the structure. A season-specific sun path diagram mapping solar trajectories in 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.

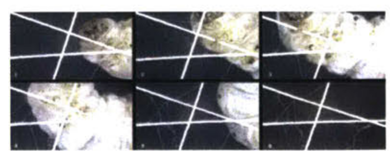

Figure 6.8: Sequence of silkworms depositing fiber on CNC deposited 0.4 mm silk thread template.

The Silk Pavilion is an initial proof-of-concept behind the synthesis of digital fabrication and biological swarm construction. The idea of controlled biological swarms was successfully tested; by manipulating *Bombyx mori* silkworms into spinning flat areas on a large-scale predefined CNC-woven silk thread scaffold structure. Experiments leading towards the Silk Pavilion are discussed in this section as a potential path towards the manipulation of 'biological builders' in achieving goals in swarm construction and biological fabrication.

6.2.1.1 Study of silkworms prior to the Silk Pavilion

Silkworm cocoon construction can be divided into two stages: parasitic scaffolding and the cocoon construction process. Fiber-placement in these two phases differs greatly in material quality, organization and function. As the silkworm constructs the scaffolding it 'parasites' to its environment, attaching fibers and pulling them across to connect to another part of the space repeatedly, building up a 3D web. In the second stage it builds its cocoon in a figure-8 pattern, building up wall thickness for the cocoon by constantly reconnecting the fibers locally inside the previously built scaffolding.

Initial explorations began by tracking the motion of a silkworm during cocoon construction as described in chapter 4.

6.2.1.2 Spatial Templating Experiments

Initial behavioral spatial experiments were conducted in order to manipulate the silk deposition. 80 mm x 80 mm flat plates were used as a silkworm spinning platforms. Varying spatial configurations of poles on top of the platforms, which were 2 mm in diameter, modified each platform. These experiments helped in guiding the parameters later used for the pavilion design and tool path design of the scaffolding structure. As can be seen in Figures 6.13, the silkworms were greatly affected by these simple spatial parameters and minimum and maximum 3D configurations could be established. However, in order to scale up, another method needed to be invented to guide silkworms across larger surfaces without creating a massive solid structure first. First experiments on thread scaffolds were successfully conducted as can be seen in Figure 6.10, providing the basis for the Silk Pavilion scaffolding structure. These first manually fabricated scaffolds further informed the constraints later to be implemented in the computational design of the scaffolding super-structure.

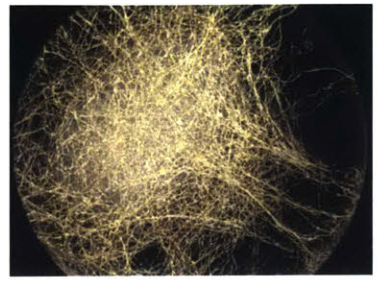

Figure 6.9: Gold sputter coated silk scaffold for SEM imaging.

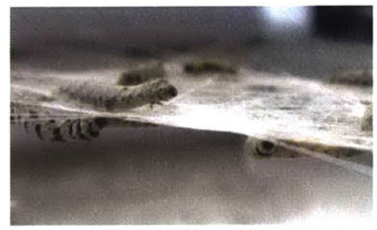

Figure 6.10: Silkworm spinning on sparse scaffold structure.

6.2.1.3 Discussion of the Silk Templating

I believe that the paradigm of using the tools that Nature provides to build in a sustainable and efficient way can lead towards both product and architectural opportunities in fabrication. Further experiments were done, focusing on the product scale for applications in the textile/garment industry. The processing of silk today involves a very long chain of different processes; in contrast, imagine the potential of digitally fabricated sparse scaffolding structures with silkworm swarms being deployed directly to fabricate the garment. The combination of a digitally fabricated scaffolding structure and the silkworm swarm could potentially be very beneficial in terms of the environmental impact of the product as well as opening up new flexibility in terms of the mass-customization of products. Introducing more complex 3D geometries could further the initial steps taken in the Silk Pavilion, creating more sophisticated guiding controls for the silkworm swarm to follow. Development and further research undertaken into how silkworms can be guided more precisely by temperature and light control will be discussed in a following section (6.2.3.1) of this chapter. The Silk Pavilion shows that the robotic control of guiding elements and the weaving of complex scaffolding structures can be developed also on a smaller and more precise scale with the goal to produce wearable garments directly made by biological swarms of silkworms. The paradigm of optimizing fibrous structures using silkworms was demonstrated, however only further developments may show the real potential of these initial experiments. The Silk Pavilion serves as the first case study for this research, establishing the groundwork for biological templating for Design.

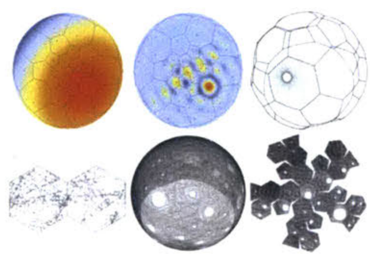

Figure 6.11: Computational mapping of temerature and sunlight parameters for the generation of the final Silk Pavilion 'super-structure' design. Image: Jorge Duro Royo, Mediated Matter.

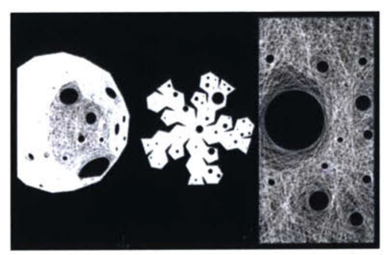

Figure 6.12: Geometrical computation for toolpath design by Jorge Duro; Left: A CNC-woven 12 diameter canopy emulating silk cocoon construction in construction scale. Middle: Unfolded distribution of CNC-woven patches. Right: Detail of CNC-woven pavilion construction. Image by Jorge Duro Royo, Mediated Matter.

In the Silk Pavilion, the process of biological templating was demonstrated on the level of the organism via a computationally deposited fiber scaffolding structure (Oxman, N., et al. 2014). By letting the silkworm spin on top of prefabricated scaffold structures, we were able to modify the silkworm's spinning behavior and generate 2-, and 2.5-dimensional fiber structures with varying geometrical and structural features informed by the shape of the scaffold. In the full-scale structure, the Silk Pavilion, the silkworms were positioned on top of a large-scale robotically spun silk scaffold as they connected a loose non-woven thread structure into a continuous skin surface. The overall shape of the Silk Pavilion was defined by the dome-shaped scaffold structure; the apertures within the dome; as well as the fiber distribution patterns designed across its surface. Once deployed, the silkworms—their trajectory, distribution and spinning routines—were governed and informed (i.e. "template") by the scaffold. Locally however, the silkworms were loosely controlled by the underlying scaffold thread structure. As a result, density gradients could be observed globally but were clearly not well controlled locally (Figure 6.14) but instead the silkworms themselves compiled material in the natural pattern of a figure-8 configuration.

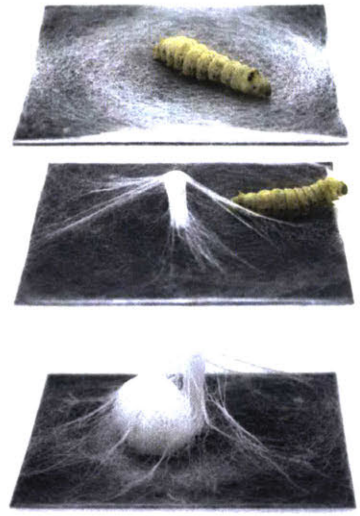

Figure 6.13: Behavioral experiments altering spatial parameters, determining height threashold. Image: Mediated Matter.

In Nature, the silkworm *Bombyx mori* spins a cocoon from approximately one kilometer of extruded silk filament (Zhao et al. 2005). It initiates the construction of its cocoon-building process by attaching a scaffold structure to its environment. This process involves the triangulating of silk thread in a corner or between twigs; within which the silkworm spins its cocoon. Behavioral changes associated with the biological process of the silkworm's fiber deposition were achieved by reducing to zero (or otherwise completely eliminating) the third dimension (height) from the silkworm's immediate environment. The silkworm is in constant movement as it travels the XY-plane (locally), and searches for the height dimension to initiate scaffold triangulation; in its absence, it will spin a close-to-flat cocoon. Experiments in spatial templating (Oxman, Laucks, M., et al. 2013) as can be seen in Figure 6.13 where the maximum threshold was established, associated with the height dimensions below, which a 3D cocoon construction will not take place. The results demonstrate that a right-angle corner could have a maximum height of 18 mm in order to maintain flat fiber deposition. In terms of the design of any global template, this constraint remains as a starting point for further investigation of more controlled local fabrication using silkworms. Also, a global template is always required because the silkworms require a structure to walk on as determined in previous experiments.

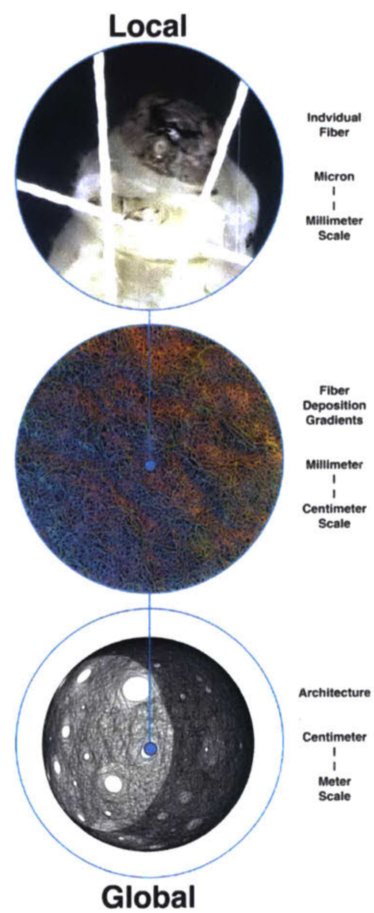

Figure 6.14: Local to Global material deposition hierarchy.

The *Silk Pavilion* establishes the tools required for biological templating for Design, by experimentally studying an organism, extracting some basic principles to be altered for fabrication and Design, and computationally designing as well as digitally fabricating a template deploying the organism with a predestined/designed product outcome as result.

6.2.2 Technological Templating for Biology: The Synthetic Apiary as Case Study (Environment)

The Synthetic Apiary (Figure 6.15) presents a case study for technological templating for biology. Here, a 'perpetual spring environment' was designed and implemented for bees (specifically the European honeybee—*Apis mellifera*) to thrive all year round. Bees are seasonally dependent, only leaving the hive and actively breeding and foraging in temperatures above 5C and humidity levels above 50% relative humidity (RH). Environmental factors such as light, temperature and humidity were closely monitored and altered to create spring-like conditions inside the Synthetic Apiary while temperatures dropped below zero outside.

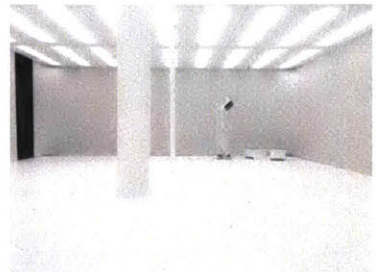

Figure 6.15: The Synthetic Apiary.

Figure 6.16: European honey bees, *Apis mellifera* building fresh wax structures inside the artifical space. Image: Sunanda Sharma, Mediated Matter.

At the core of this experiment is the creation of an entirely synthetic environment enabling controlled, large-scale investigations on the hive level. The future goal would be to integrate biology into an architectural environment, for the combined benefit of humans *and* eusocial organisms, reintroducing Nature into the city via a new kind of architecture. However, this project ended before it really started to be used in its full capacity as the experimental environment it was designed for—to study and experiment with bees, investigating distributed fabrication in flying insect swarms. While this experiment was cut short it still presents valuable insights into how to condition a completely artificial environment for a biological fabrication system in terms of light, temperature, humidity, and artificial nutrients. Flying insects present unique challenges as the containment and spatial requirements are difficult to provide and maintain. The observation of breeding activity and the building of fresh wax structures in the Synthetic Apiary points towards the successful implementation of a technological template for biology. Further investigation in fabrication as well as fine-tuning of the environmental factors is required for successful technological templating with a manipulated fabrication result.

Figure 6.17: SEM of Apis mellifera, European honey bee. Image: James Weaver, Harvard WYSS Institute.

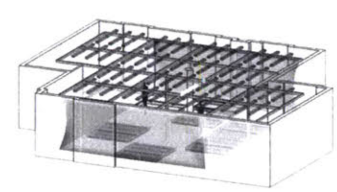

Figure 6.18: 3D model of the Synthetic Apiary.

An entirely sealed tensile structure (Figure 6.18 and 6.19) within the 200m2 experimental space was designed and built using a framework of wooden crossbeams stretched between white elastic fabric (Dazian Trapeze Plus white 122", 90% polyester 10% Spandex), above which full spectrum low-heat lights (144 'Spectra Brite' full spectrum 48" fluorescent tubes, 32 watts, 93 cri) were fixed (Figure 6.19). This allowed for a large space for habitation and foraging with minimal crevices and corners, as well as easy viewing of hives as well as individual bees. Additionally, it provided a bright space with dispersed light to mitigate one commonly seen issue in greenhouses, in which honeybees are attracted to light and injure themselves through repeated contact. The architecture of the space consisted of a central rectangular sealed enclosure with two entrance rooms. Each entrance room had netted magnetically self-sealing doors into the main enclosure as well as to the outside parameter of the entire enclosure, thus preventing dislocation of bees. The concrete floor of the enclosure was cleaned and painted white, and was swept and mopped every two days with low concentration bleach in hot water. Eight wooden Langstroth hives (approx. 160,000 total) of European honeybees, *Apis mellifera*, were introduced (Best Bees Company). Each hive had 1-3 boxes, each of which had 10 frames with foundation wax. Climate conditions were maintained at between 50-70F, at least 50% RH, 15 hours simulated and incremental daylight, and appropriate air circulation and ventilation; this mimicked a spring-like natural environment, during which bees are highly active. This may also be tuned to represent other seasonal climates during which particular behaviors and activities may be observed. The system features standard residential heating, a heating ventilator unit, bladeless fan (Dyson AM03 Air Multiplier Bladeless Adjustable Pedestrial Fan), plus space humidifiers (AIRCARE HD1409 Digital Whole-House Console-Style Evaporative Humidifier) and additional electric heaters as needed. Air quality was additionally improved by exhaust vent fans (Panasonic FV-15VQ5 WhisperCeiling 150 CFM Ceiling Mounted Fan) as well as by a fresh air ventilation unit (Panasonic FV-04VE1 WhisperComfortTM Spot ERV Ceiling Insert Ventilator). The air quality may also be tested and monitored to ensure a healthy environment. Nutrients and water were provided in abundance in a central foraging area. Pollen substitute (BeePro) and 1:1 pure sugar water (supplemented with HoneyBee Healthy to prevent fermentation) were provided in trays equipped with wooden posts for cleaning, or floating colored foams to prevent drowning, respectively. All nutrient sources were disease and pesticide-free, and replaced regularly to ensure quality. Hives were also regularly checked for presence of pests such as mites (*Varroa* sp.) and hive beetles (*Aethina* sp.), as well as signs of viral diseases such as deformed wing virus. Used wax frames may also be tested for pathogens, and products could be evaluated for material composition. Researchers were all trained and approved by Massachusetts Institute of Technology Environmental Health and Safety, in partnership with Best Bees Company, and wore protective mesh and fabric suits, along with gloves and boots (Mann Lake Ltd.), while inside the space. Out of the eight hives, two were established as stable controls, and basic experiments were initiated in the others, such as frame removal, wire foundation insertion, and removal of natural stored honey to encourage wax and honey formation.

Figure 6.19: Synthetic Apiary during construction. Image: by the author.

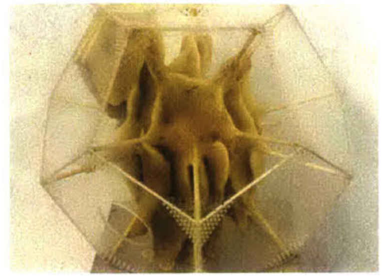

Figure 6.20: "Yuansu II" beeswax sculpture by artist Ren Ri, demonstrating gravity control over wax formations made by bees. Image by (Pearl-Lam-Galleries 2017).

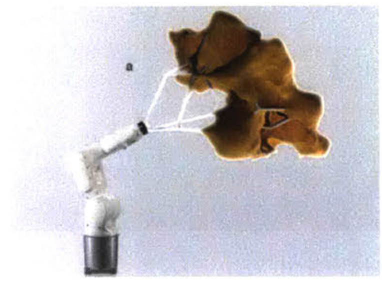

Figure 6.21: Illustration of potential fabrication templating using a robotic arm (a). Image: In collaboration with Christoph Bader, Mediated Matter

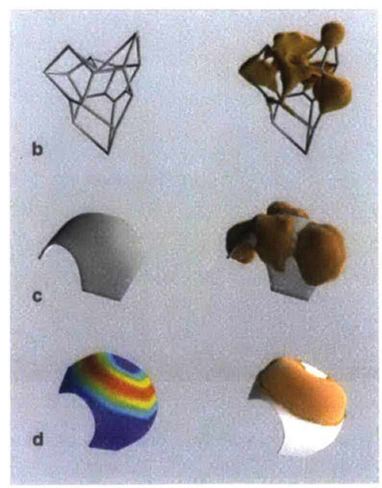

Figure 6.22: Illustration of potential fabrication templating using a robotic arm, spatial templating and gravity (b), light templating (c), temperature templating (c). Image: Christoph Bader, Mediated Matter.

6.2.2.1 Towards Technological Fabrication Templating

Being able to control an environment is only the first step towards controlled swarm fabrication using honeybees. Artist Ren Ri and Tomas Libertiny's sculptures provide great examples of what may be achievable, however they are limited in their analog Nature and a controlled space as well as digital fabrication tools could clearly provide a significant step towards direct control over a bottom up biological fabrication system.

As briefly discussed in a previous section of this thesis, Ren Ri was able to manually template bees' building abilities creating stunning three-dimensional outcomes half sculpted by bees and half by the artist. Here the question arises, what if you could create a digital template that could take this manual operation into the digital biological fabrication strategy. For this mind experiment, we have to first understand how these structures were influenced by the artist in order to get specific shapes. Ren Ri has a very interesting approach to templating bees—gravity. First he gives the hive's enclosure a specific form as well as wooden and/or acrylic guiding rods for the bees to start building the honeycomb wax structures on. Then he sequentially rotates the whole hive after weeks of building vertically downwards, each time giving the bees a new spatial constraint in terms of wooden attachment points as well as gravitational guide, providing a new orientation for construction (Pearl-Lam-Galleries 2017). To bring this into the digital realm a 6-axis robotic arm may serve as the digital motion platform having an end effector which is a whole hive of bees, harvesting their environment for nutrition and building material while the digital motion platform serves as a guiding principle of construction, as it may rotate continuously slowly over time, sequentially, week after week or even in a feedback loop, 3D scanning the build structure each day and giving feedback for calculating the next move of the robotic arm in order to achieve a specific outcome, as shown in illustrations in Figures 6.21 and 6.22.

6.2.3 Biological Augmentation for Design: Silk Flock and Synthetic Environment for Light-guided Ants as Case Studies

6.2.3.1 Silk Flock

In continuation of previously discussed behavioral experiments with silkworms, the first case study—exploring the biological augmentation for Design—aims to implement a rule-based system in a non-communicative and non-distributed biological system. Here, silkworms are studied further in a quest to combine their ability to produce a highly tunable material system with distributed fabrication logic.

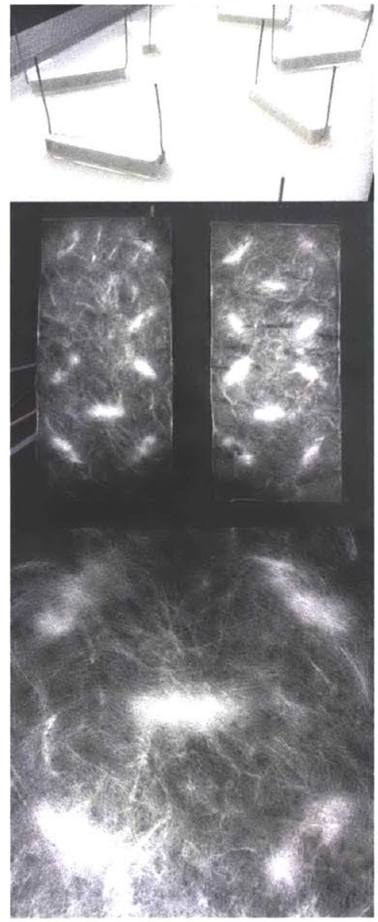

Figure 6.23: Power resistors imbedded in silicone substrate showing clear correlation between temerature and silk deposition.

In initial experiments a direct relationship between surface temperature and the density and physical properties of fiber deposition was demonstrated. In these experiments, silkworms were placed on flat surfaces, with underlying power resistors. As seen in Figure 6.24, a single resistor was embedded into a circular glass sheet and black paper was glued onto the surface. The resistor created a thermal gradient on the glass surface, ranging from room temperature (approx. 21°C) on the outside up to 140°C in the center of the disk. Three silkworms were placed onto the surface near the edge of the disk and deposited a density gradient of silk fiber around the central hot zone, leaving the 'hot zone' free from silk and creating a gradient towards the outside edge of the disk. What is interesting to observe is the counterintuitive approach of the silkworm to create a denser deposition around the hot zone, almost as if it was designed to insulate itself against the heat; and less dense areas at the outside rim of the disk at room temperature.

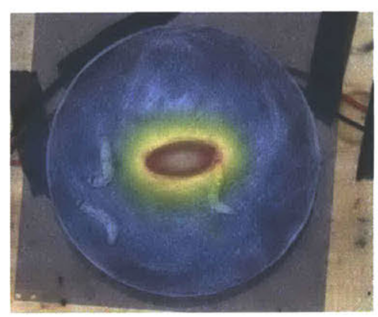

Figure 6.24: Central 'hot zone' temperature gradient matching silkworm silk deposition. Image: Will Patrick, Mediated Matter.

Further experiments with multiple resistive heating elements were carried out in order to correlate between pattern formation and an underlying temperature grid, as can be seen in Figure 6.23. Ten silkworms were placed on a rectangular surface, and spun denser areas where there was a heating element embedded underneath. Less dense areas were observed in between and around the warmer areas. Here, the temperature was much lower (comfortable to the touch), which resulted in closed patterns leaving no clear areas, as the temperature was tolerable for the silkworm throughout the underlying surface. What these preliminary results show is a clear *correlation between temperature and spinning behavior* to create density gradients on a given surface. However, these were single experiments; further verification will be needed to achieve conclusive results. Also, these experiments lack discrete temperature control of individual heating elements and three-dimensional global surfaces (scaffolds), or feedback control loops and computational control. Individually addressable arrays of resistors, projection of thermal patterns or distributed robots could potentially direct the silkworms across surfaces or scaffolding structures, enabling computational control over the organism.

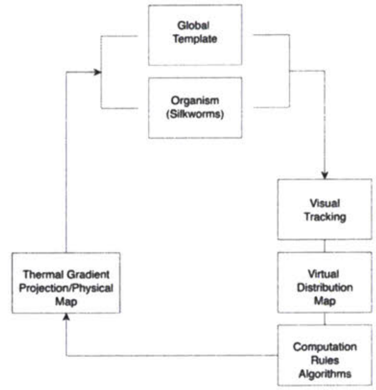

Figure 6.25: Process approach feedback loop flow chart.

The flow diagram shown in Figure 6.25 shows a potential experimental workflow to introduce computational control to the gradient patterns formed by the silkworms. A global template is populated with silkworms, which are tracked by cameras feeding location data onto a computational map. This dynamic map, showing the silkworms' distribution across the global template, can be mapped to a desired shape showing the discrepancies of actual state and desired outcome. This information can be taken as input for changing the thermal gradient by individually addressing the underlying resistor array embedded in the global template, thus directing the silkworms to a desired location.

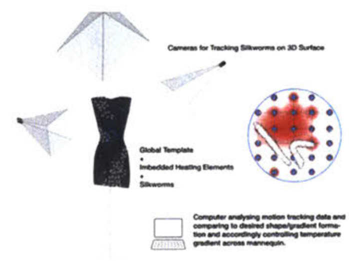
Figure 6.26: Diagram of possible application to make garment via feedback loop implementation with tigjht spatial control over fiber deposition.

The following section illustrates how the above cycle can be used in the context of digital fabrication. To achieve this, a mannequin serves as the 'global template' (Figure 6.26) and ready-to-spin silkworms are placed onto it. Resistive heating elements are embedded into the global template (mannequin) in an equal grid formation and their temperature can be addressed individually via computational control. Multiple cameras are used to track the movements of the silkworms on this three-dimensional global template. The tracking information creates a virtual map, which can be used as actual location data relating to the silkworms, and can be mapped through the control of the embedded heating element grid to a desired formation and thus deposition of silk fibers across the surface of this global template. This process could be programmed to run in a loop, potentially using an algorithm to react to the actual and the desired formations until a desired shape/density gradient is established. In this experiment, the Design approach *shifts from templating to augmenting* the silkworms, since logic could be introduced which drives the behavior of the silkworms and their fiber deposition for fabrication.

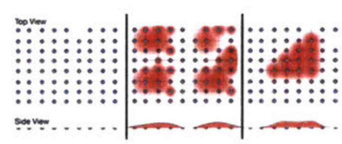

Figure 6.27: Possible fiber deposition control and distribution.

The range of shapes achievable is a combination of the global template (*i.e.* static templating) and the embedded heating element grid density or thermal projection (*i.e.* dynamic templating). The global template can be any given three-dimensional surface with the constraints discussed in earlier research (Oxman, Laucks, M., et al. 2013), where the internal radii of any given curve need to be more than 50 mm to prevent silkworms from initiating cocoon building activity. Local patterns can be achieved in the form of density and thickness gradients of the resulting fabric over time. Here, the density of the underlying heating elements is the main constraint for pattern complexity (Figure 6.27). While these projections are not realized in practice, the initial steps taken towards the realization of these concepts have been taken and will continue in the Mediated Matter group, proving these ideas in the near future.

6.2.3.2 Light-guided Ants

The second case study for Biological Augmentation for Design focuses on experimentation with harvester ants (*Pogonomyrmex occidentalis*), which was carried out to establish a controlled manipulation of path trajectories in tunnel formation and accumulation of ants. Different guiding stimuli were tested such as vibration, magnetism and light. It was found that light had significant impact at wavelengths of 405 mm. Immediate response was observed when pointing a light emitting diode (LED) light source onto the surface of the ant arena. Ants were drawn to the light source and large accumulations of ants would occur where ultraviolet (UV) light was present. In further experiments UV light was used to guide ants across 2D surfaces, and create shapes (circles, lines, squares) by accumulation with a UV scanning laser projector (Figures 6.28, 6.29 and 6.30).

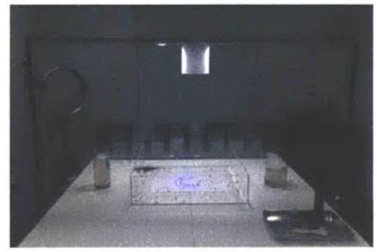

Figure 6.28: Ant lab, ant arena, UV laser projection, hydrogel experiments.

Figure 6.29: Ants accumulating around projected UV laser circle, 00-23 seconds.

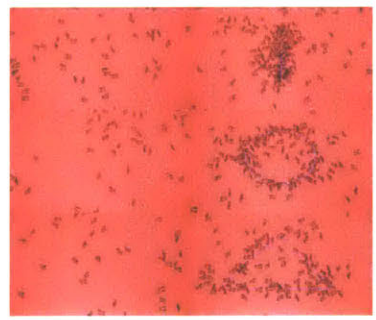

Figure 6.30: Ants accumulating around UV scanning laser in specific shapes (line, circle,triangle).

Also, rectangular three-dimensional, semi-clear hydrogel environments were used to investigate tunnel formation with single and multiple UV LED point light sources present. The initial results showed that not only would ants accumulate according to the placement of a UV light source in a two-dimensional arena, but they would also 'tunnel' through the hydrogel media towards a light source. This phenomena was further investigated by using a small robotic arm attached on the outside of the hydrogel environment with a single UV LED light source attached, making it possible to change the position of the stimuli source over time as shown in Figure 6.31 and 6.32.

Figure 6.31: Synthetic ant environment, robotic arm UV path guide control.

Results showed clear correlation between the three positions of the robotic arm and tunnel formation in the hydrogel by excavation through the ants. This case study may create another potential opportunity to dynamically control the robotic arm—and thus the stimuli—in accordance to tracking data acquired from visual scanning of the hydrogel environment, providing an access point for integrating an additional logic to the ants' behavior. While the ants already collaborate in their fabrication—with or without additional stimuli—path trajectories and potential computing of more optimal structural geometries may be introduced through this method.

Positive casts were taken from the 3D tunnel formations in urethane resin plastic (Figure 6.34), and one test was cast in bismuth, a low-temperature metal casting material. Here, the element of material tunability is present in the excavated geometric network of tunnels, while the resulting product casting material is still very homogenous. Future development may include integrating the feedback loop discussed previously and introduction of a new material system, which may be a biological one. A bacterial culture may be introduced to a completed tunnel network, which would be able to feed off the already existing hydrogel and potentially build biofilm tubular structures templated formally by the excavated tunnel network, bringing multiple research thrusts of this research framework into play.

Both the silkworm and ant case studies are incomplete in terms of closing the feedback loop creating a truly dynamic fabrication system. However, research currently conducted in the Mediated Matter group will continue 'closing the loop' in order to demonstrate these concepts in practice for TAB (Technological Augmentation for Biology).

6.2.4 Technological Augmentation for Biology: Future Directions

The final thrust in this research framework shall point towards future directions that may be informed by this thesis. The work imagined may include all four thrusts in different capacities, feeding off of Nature for energy and material resources through efficient organismic conversion of energy for material production in a designed environment for product outcomes on the large scale. This may be achieved by genetic modification of organisms (*e.g.* microorganism such as *E. coli* bacteria or larger organisms such as silkworms for example for a modified version of the fiber matrix sericin to be water resistant) for modified product output. Other means may include fully autonomous robotic swarms working together with biological distributed fabrication systems for designed outputs. Finally, there are various potential ways to augment living systems via electronic implants to guide behavior for fabrication. Imagine—for example—a swarm of autonomous fiber winding robots weaving architectural structures, feeding off solar energy and harvesting material from their immediate environment. The structure may be induced with bacterial cultures starting a *secondary* growth process connecting individual strands of the robotically fabricated structure into adaptive membranes; living and reacting to environmental changes over time. A hierarchical colony structure may be imagined where flying weaving robots, ground harvester robots and climbing builder robots construct the materially graded and designed scaffold for biological systems, of microorganisms as well as larger organisms such as ants, termites and bees to thrive on, completing a holistic distributed fabrication approach of merging the natural with the technological.

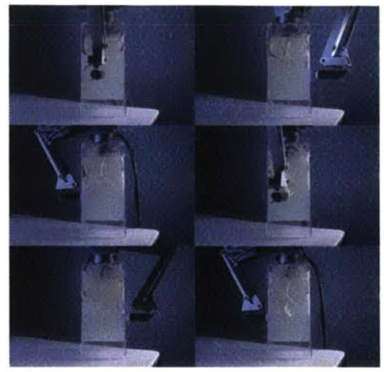

Figure 6.32: Ants building in hydrogel 3D tunnel formations guided by robotic arm and UV (405nm) light.

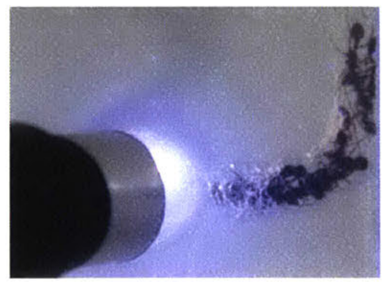

Figure 6.33: Close-up view of ants following the robots UV light source.

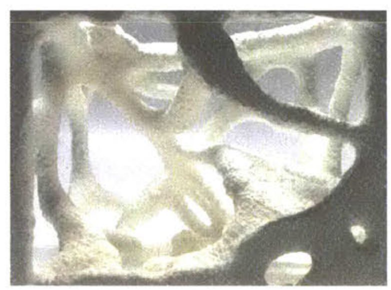

Figure 6.34: Cast of synthetic ant environment after robotic guiding procedure.

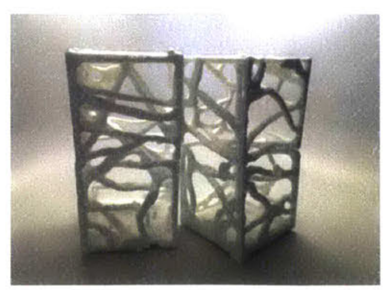

Figure 6.35: Stacks of four casts of synthetic ant environment after robotic guiding procedure.

6.3 Conclusion

The framework—with its four research thrusts—has been implemented in four case study projects.

I have demonstrated four case study projects: the Silk Pavilion, the Synthetic Apiary, Silk Flock, and Light-guided Ants. While templating has been successfully shown in the Silk Pavilion and the Synthetic Apiary, in practice only the basic steps towards augmentation have been demonstrated. Further applied research will be conducted to validate augmentation as laid out in this chapter by testing multiple patterns with an experimental setup in which silkworms are templated across a physical adjustable thermal gradient map, enabling computational augmentation of their behavior, proving these concepts beyond my PhD.

In the following chapter I will discuss my final project for this thesis—the Fiberbot project. This project is my first attempt at tackling the problem of scale as well as the problem of material tunability for the large scale in digital fabrication through a distributed robotic system.

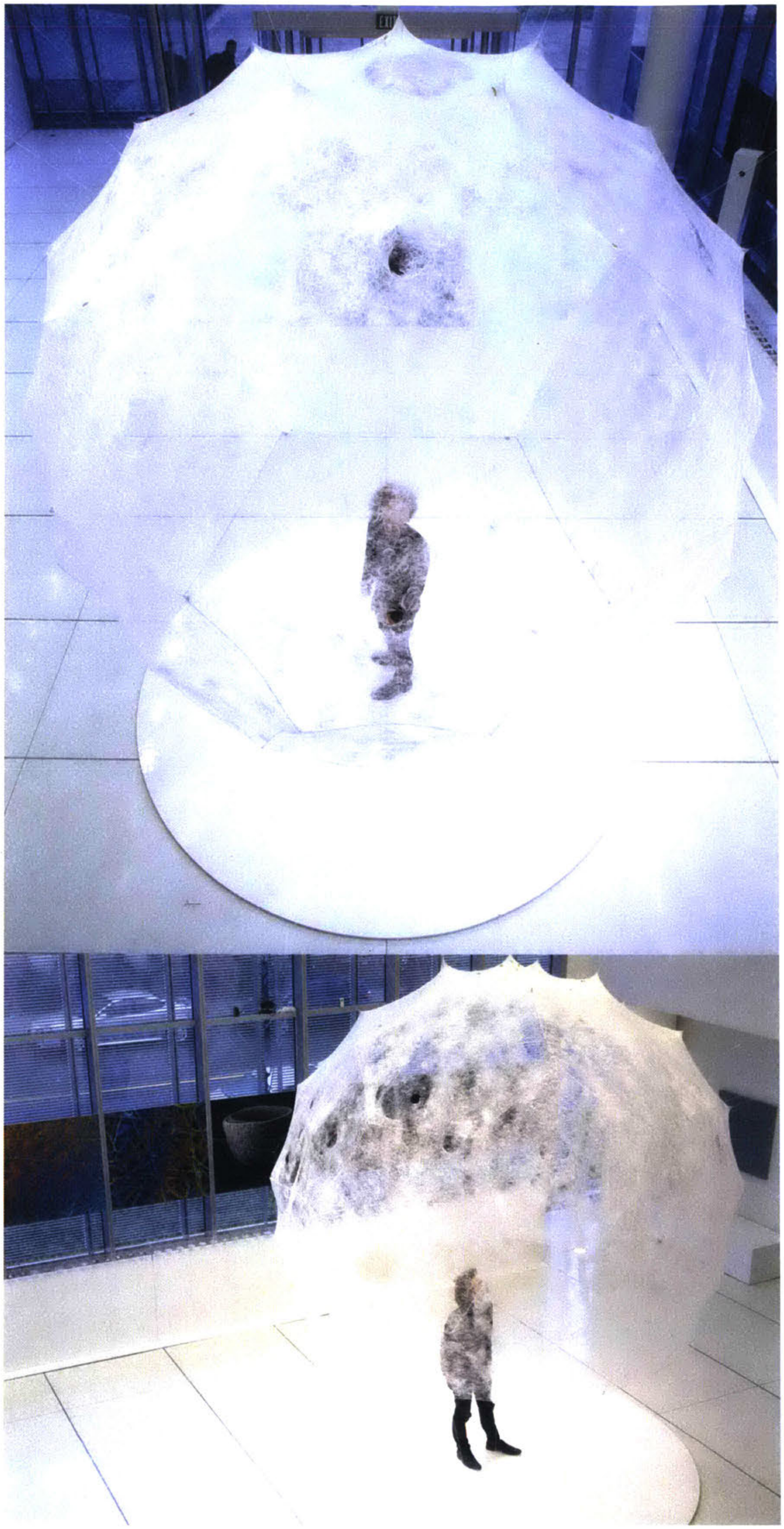

Figure 6.36: The Silk Pavilion in the MIT Media Lab, Mediated Matter. Image: Steven Keating

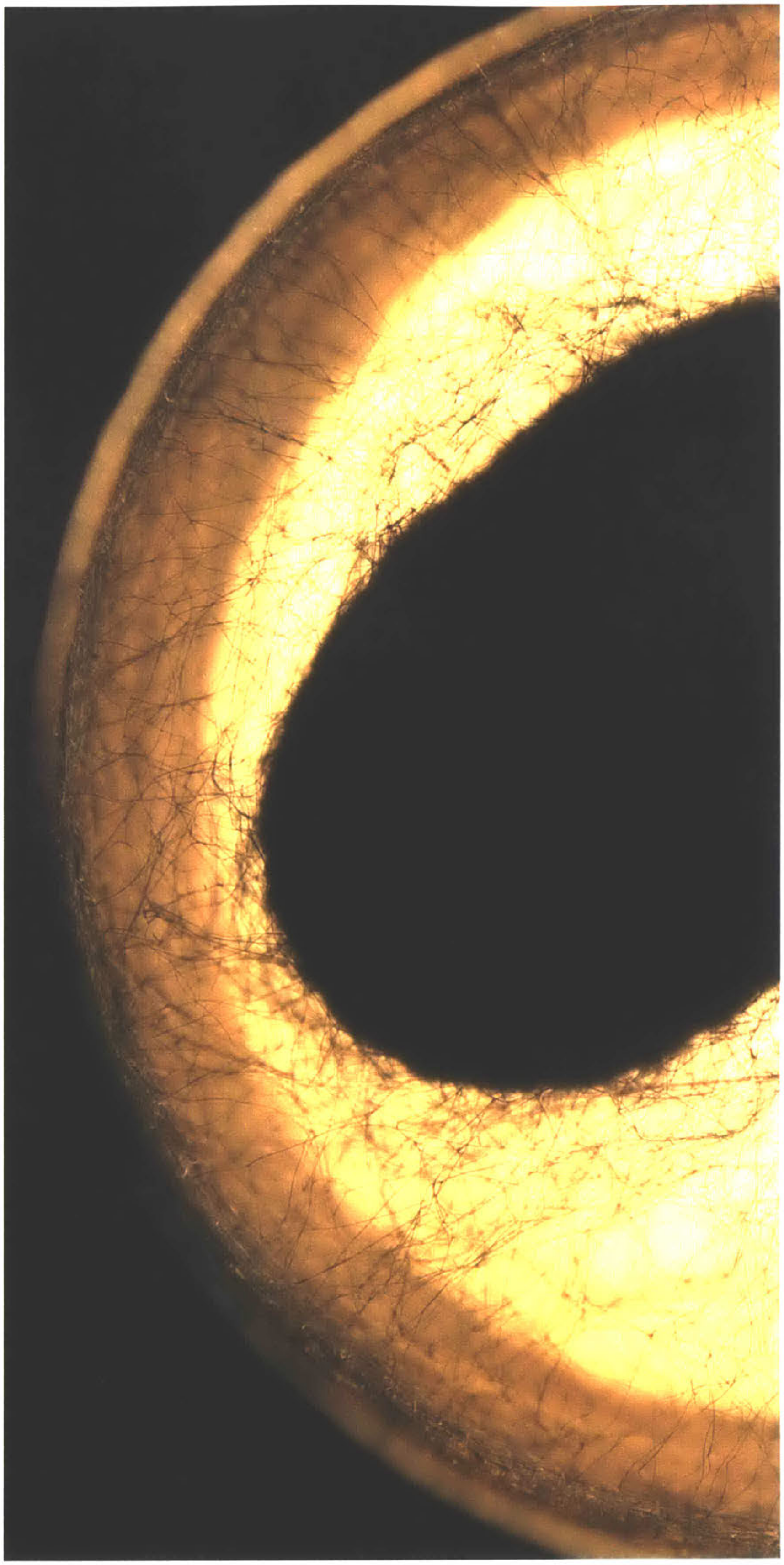

Figure 6.37: Silk cocoon, gold sputter coated for SEM imaging.

Figure 6.38: The Synthetic Apiary.

Figure 6.39: Bees building fresh wax structures inside the Synthetic Apiary. Image: Sunanda Sharma, Mediated Matter.

Figure 6.40: Ants being guided on 2D surface by UV light.

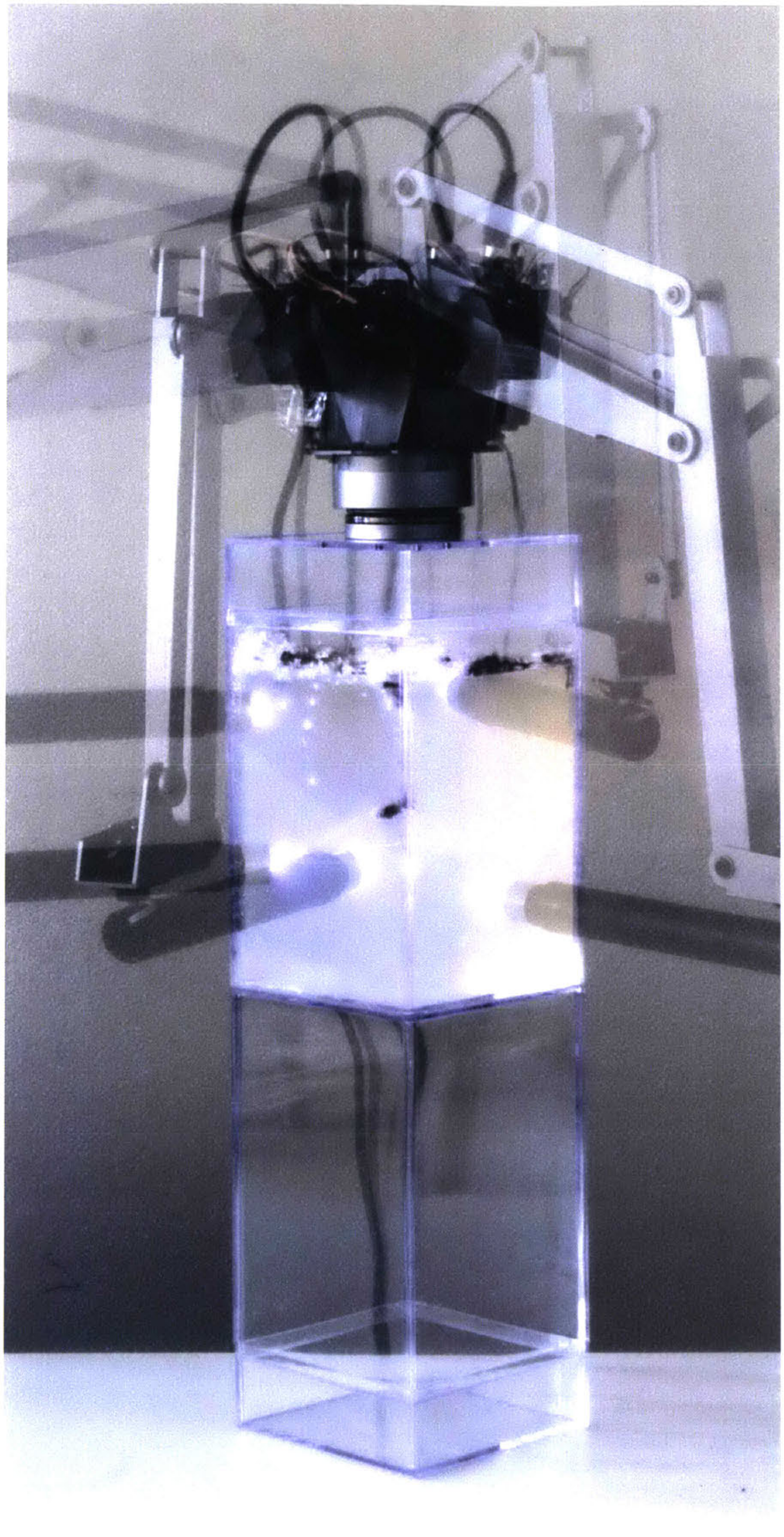

Figure 6.41: Ants being guided in 3D medium, controlling tunnel formations.

Chapter 7

Fiberbot—Agent-based Composite Construction Platform: Distributed and Materially Tunable Robotic Fabrication across Scales

7.1 Introduction

We introduce a novel distributed robotic construction system that is able to build a self-supporting architectural structure collaboratively, from fiber composites. A 20 (16) robot system is presented, able to build and climb its own tubular structures, which—over time—become single threads within a larger construction network of an emerging architecture. The use of fibers as a construction material can achieve high degrees of variation by embedding functionalities into the built structures. Fiber composites are lightweight and can achieve high structural performance (Joshi et al. 2004). Additionally, there is an exciting potential to embed various functionalities through the use of different fibers such as fluidic channels for heating and cooling of the structure, light guides for illumination, data transfer and conductive fibers for electrical applications. Here, the building material becomes a woven 'fabric' of various materials and functionalities that exists within a single construction process.

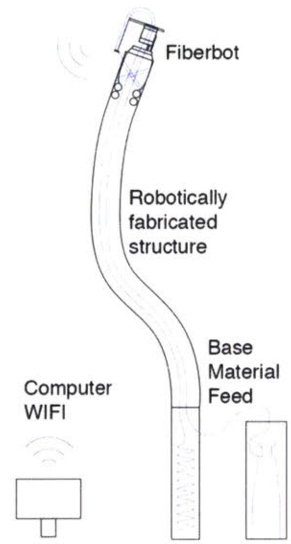

Figure 7.1: Illustration of basic Fiberbot system approach. Illustration: Laia Mogas, Mediated Matter.

A common robot operation sequence is: inflate silicone membrane, start fiber-winding and resin-feed-pump, turn on UV LED's, deflate, stop fiber-winding, drive robot up, orient robot in 3D space according to IMU data and repeat sequence.

Figure 7.2: Final robotically fabricated installation in front of the MIT Media Lab E15.

All robots are sent instructions wirelessly from a central computer, while power and material is fed up through to the tube it makes; however, the hardware required for local communication between robots is already integrated for future deployment, potentially embedding hierarchies in the communication protocols and algorithmic decision-making informed by onboard sensing.

7.1.1 Vision

Figure 7.3: Final installation structure photographed against sunlight showing the translucency of the columns.

A conventional building site today arguably could be considered a multi-agent distributed system of varying degrees of hierarchies. From armies of computational designers in architectural and engineering offices to armies of material fabricators and distributors to 'swarms' of construction workers in cranes and diggers to painters, carpenters, plumbers and electricians to name just a few—a skyscraper truly requires massive hierarchical and organized effort of hundreds of individuals collaborating on a single objective. However, automation only plays a minor role in construction hardware on today's building sites. Although automation has arrived in the supply chains of prefabricated parts, at least to a certain degree, on-site construction is largely manual and or using manually operated machinery. In research, significant efforts and advances have been made to automate conventional and previously manual construction processes such as brick laying (Raković et al. 2014, Dörfler et al. 2016) or concrete-filled foam work construction (Keating et al. 2014), facilitating previously difficult or even impossible new forms and functions. These new technologies largely rely on large robotic arms—a technology widely used in the automated construction of products in the auto industry—as well as aiming at the automation of conventional construction. Although these examples result in impressive structures, conceptually they are not tackling large-scale construction, as they are physically limited in their construction reach (height). For truly scalable fabrication systems, we need look no further than the previously discussed eusocial insect builders such as termites, ants and bees to understand that in order to achieve truly automated and large-scale construction we need smaller machines that can collaborate with each other, rather than larger machines.

In the following section, I introduce the Fiberbot project, which addresses some aspects of this complex vision of large-scale construction automation, which not only tackles scale but also aims to bring about new forms and capabilities of varying material distribution, which are largely absent from current construction.

Figure 7.4: Industrial glass fiber composite filament winding machine, 'LAM-TECH Mandrel-Lamellar Machine Continuous Winder' by VEM Technologies. Image: (VEM-Technologies 2017)

7.2 Background: History of the Fiberbot Development

7.2.1 The Idea

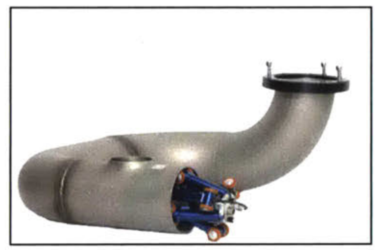

Figure 7.5: Pipe Inspection Robot, 'Agility Pipe-Crawler' by OMS company. Image: (Optical-Metrology-Services 2017)

The silkworm showed us how to construct beautifully and efficiently with a fiber composite system from the inside out. The Fiberbot project borrows this general idea found in Nature, reinterpreting the concept of the body sitting inside the structure it makes, thus acting as a mold. The first experiment with fiber composites was the cable-suspended robotic system (discussed in Chapter 4), which explored UV-curable resins and fibers as a potential material system for the end effector. The ideas from free-form 3D printing and robotic arm fiber construction also feed into and culminate in this project. The initial idea was to pull fibers vertically upwards while a tight silicone sleeve was pulled up, curing resin surrounding the fibers on the fly. Although this idea was abandoned for the cable-suspended robot project, a robotic fiber composite construction system stuck as a promising material system for a structurally sound method for the large scale. Another inspirational starting point was the project 'Phantom Geometry' (Hasseln and Hasseln 2012), a master's thesis in architecture by Kyle von Hasseln and Liz von Hasseln, developed in the Robot House at the Southern California Institute of Architecture (SCI_Arc). This project used UV-curable resin and a light projector, 3D printing from the ceiling downwards using a robotic arm as motion platform. Here, a scaffolding structure was still required—the beautiful, stalactite forms attached to and 'grew' from the building's ceiling. We also discussed ideas for fused deposition modeling (FDM) 3D printers to climb their own structures in order to build taller structures by removing the frame. These ideas finally culminated in the idea of the Fiberbot, which draws inspiration from the silkworm's fiber matrix material system while varying material properties on the fly. Industrial and robotic inspiration comes from pipe inspection robots (Horodinca et al. 2002) and conventional filament-winding machines (Shen 1995). As the name suggests, pipe inspection robots inspect pipes; thus their main capability is that they are able to drive inside tubes. Some can also go around corners while carrying sensing equipment such as cameras. For the robotic material system, industrial filament winding seemed a promising example for creating density gradients in tubular structures, as the winding patterns could be tightly controlled and adjusted to create varying structural properties in a fiber/matrix system.

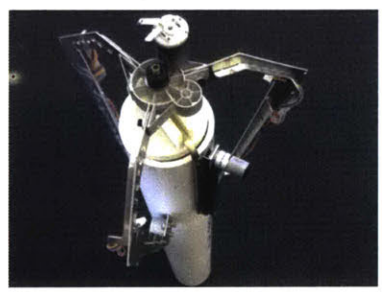

Figure 7.6: First prototype of the Fiberbot, external drive mechanism.

Figure 7.7: Second Fiberbot version with three wheel servo drive and linear and rotary servo control. Instead of the inflatable expandable mandrel design indroduced in later versions, this robot uses a mechanical expandable design.

7.2.2 Initial Fiberbot Prototypes

The focus of early Fiberbot prototypes was to establish the basic functions of driving upwards (climbing) and combined rotary and linear motion (winding). The first basic robot design externalized the climbing function via three arms (Figure 7.6), motors and wheels on the outside of the tube while the mandrel hung internally. In between the outer tube and external drive arms, the spinning winding-arm was situated, rotating a linear actuator.

The second iteration of the robot had an entirely unique architecture. The expandable/retracting mechanism was designed to wind fiber around polytetrafluoroethylene (PTFE) non-stick tubes, which were threaded onto carbon fiber rods positioned in a hexagonal configuration. Throughout the robot's electromechanical set-up, servos were used to drive all moving parts (Figure 7.7). The rotary and linear winding motion was achieved by using a motorized linear slide potentiometer, which is commonly found in professional music and light mixing controllers. These belt drive assemblies[12] are unique in that they have integrated feedback via the slide potentiometer in a very compact format, at a low cost. However, torque is not their strength, thus requiring modification of the actuator using a larger brushed DC motor. This linear actuator drives a continuous 'servo motor' up and down, internally to the robot. The base drive assembly consists of three continuous-rotation-'servos' without feedback and only direction and speed control. Soft foam wheels were mounted to the three servos with the aim to apply enough force to the outside wall of the fabricated tube, creating enough friction to lift up the robot. This robot was only tested in dry runs (no resin was applied to the winding of fiber). However, basic functions such as winding and internal tubular driving were successfully tested.

The third robot (Figure 7.8) was the first to be fully tested in upward driving and winding while making its first tubular member. This robot design was an attempt to use 3D printing as the main fabrication method, trying to simplify later production of multiple robots. In this design, an inflatable membrane was introduced as the expanding/contracting mandrel, as the mechanical methods were harder to fabricate and more likely to fail, as many components had to function together and fatigue, especially of the nylon flexures, had become an issue. This robot used two 100 mm linear potentiometers as guide rails, which were attached to a 3D printed drive 'cube' nesting two DC gear motors perpendicular to one another, one driving a 3D printed rack and pinion for linear actuation and the other rotating a hollow shaft for rotary motion. The rotary shaft was set centrally in a sleeve bearing and an aluminum water jet arm was attached at the end providing the external winding function. The fiber feed was central as in all Fiberbot designs, while in this design iteration the resin feed was simply not developed and for early wet winding test a syringe was fixed to the winding arm with a fiber inlet and outlet wetting the fiber before

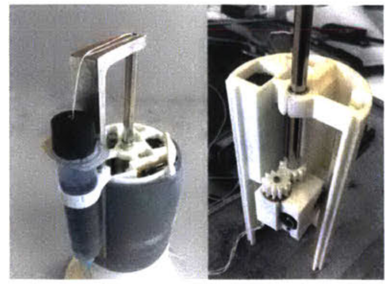

Figure 7.8: Third iteration of the robot, Left: Fully functioning robot, resin mounted on the winding arm, Right: 3D printed body and rotary/linear winding assembly.

Figure 7.9: Early 3D-printed and spring-loaded base drive assembly using geared brushed DC motors.

Figure 7.10: Water jet aluminum flexure base drive assembly using geared brushed DC motors, delrin wheels, BunaN O-rings.

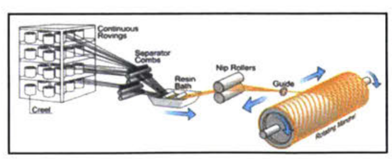

Figure 7.11: Filament winding process in industry making fiber-reinforced tubes. Reference: http://www.nuplex.com/composites/processes/filament-winding.

12 SparkFun, PN: COM-10976, Motorized 10K Linear Slide Potentiometer.

application to the mandrel.

7.2.2.1 Robot Drive (locomotion) Prototypes

The base drive for forward motion of the robot inside the tube was also the first spring-loaded design using three brushed DC gear motors.

This flexure base drive design (Figure 7.10) was intended to again minimize part count by eliminating springs and the base housing by two water jet aluminum flexures. Even though this design made sense in regard to reducing the part count it was actually time-consuming to produce on the water jet as of its intricate features and overall space constraints greatly limited motor choice. Another aspect to consider when working with flexures is that they naturally flex. As in this design they were not fully constrained; even though the pressure applied to the inside wall of the tube was sufficient to carry the robot's weight upwards, with any rotational forces applied the robot would easily drift to that side. Also, inaccuracies in the water jet cutting of the part led to some problems in regard to consistent flexing—as the aluminum cut was 9.5 mm thick in order to constrain the z-flexing, the water jet's kerf at this thickness is undesirable.

7.2.2.2 Nozzle Design and Prototypes

The nozzle had to be designed as a mixer of fiber and resin while being lightweight to reduce centrifugal forces during winding. Several iterations were designed and tested. While initial versions tried to mimic industry standards in a miniature form factor, the final version is rather simple in comparison. In the fiber-winding industry, the fiber runs across several rollers before and after running through a resin bath, making sure the fibers are sufficiently wetted as well as removing any excess resin to avoid drippage and oversaturation (Figure7.11). Tensioning the fiber at a constant force is also desirable in order to maintain a consistent packing of the fibers.

In the initial design, the fiber was pulled through five rollers, the first roller wetting the fiber as it was pulled through the resin bath, the second and third rollers stripping excess resin from the fiber, and four and five delivering the fiber to the mandrel at varying angles depending on winding arm position (Figure 7.12). While this design was arguably the most sophisticated and most closely mimicked what is done in industry, it was still too heavy to be mounted to the winding arm because it maintained a constant amount of resin. Further, the aim was to create a completely sealed nozzle design such that the robot could move freely in 3D space without leaking resin, which became a challenge, as the outlet rollers would be hard to fully seal without creating further friction on the fiber feed.

Further, nozzle iterations were designed, with one standing out as an interesting contender, providing a flexible spatially moving nozzle outlet as the fiber and resin are fed through a spring surrounded by a silicone tubular sleeve (Figure 7.13), providing a tensioner and tension release, while the fiber inlet could be fixed.

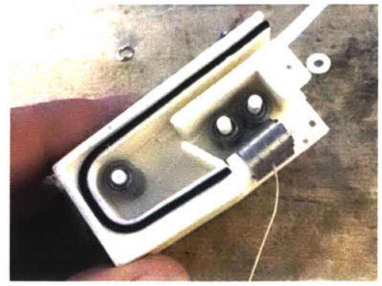

Figure 7.12: Five rollers transport the fiber through a closed resin container, open view of the nozzle design.

Figure 7.13: Tension-relieving spring-loaded nozzle design iteration.

Figure 7.14: External UV LED curing cylinder, later upgraded to internal solution.

Figure 7.15: Development of the third iteration. All electronics are tightly packed inside the robot's body.

7.2.3 First Robotically Fabricated Column

Figure 7.16: Robot set up inside starting tube for first large automated test, with three-belt-drive.

Figure 7.17: Winding around inflatable with embedded UV-curing LEDs.

Figure 7.18: Robotically fabricated tube, 180 cm in length.

The fourth and first fully functional robot (Figure 7.16) was tested in September 2016 making a 1.8-meter long straight tube (Figure 7.18). This robot version consists of a fiber-winding arm, which is actuated by geared DC motors in vertical[13] and rotary motion[14], providing the key fabrication capability. An inflatable silicone membrane, acts as a mandrel for winding and detaching the cured fiber composite from the robot's body, allowing the robot to climb to its next position (Figure 7.17). A small onboard air pump and solenoid valve [15] provide in/deflation of the membrane. Upward actuation is achieved by a spring loaded three-motor-drive-assembly[16]. The robot is controlled via an onboard microcontroller[17], (8)MOSFET shield[18], IMU[19] and a servo motor driver[20] for the linear actuator. A simple control loop was written, simply switching the states of the motors, pump, LEDs and solenoid on and off.

Resin and fibers are fed up to the robot through an initial 3D-printed foundation base running up through the tube the robot makes. At the heart of the robot is the first fluid rotary transmission enabling the resin feed and fiber in a coaxial tube to the outside of the winding arm wetting the fiber with resin at the tip, right before application to the inflatable silicone membrane. In this design, the UV LEDs for curing are sandwiched between two silicone layers in the inflatable. This iteration of the robot included most functions of the final Fiberbot design, though with limited robustness; fatigue of many parts was evident after only 1.8 m of construction, and control and feedback of winding and driving was not established in this version. In the following sections, I will describe the final version of the Fiberbot design and batch production. Four basic prototypes of the fiber-winding climbing robot (Fiberbot) have been designed and built to test singular robot operation. From this last initial successful test of a single column we were able to project what functions needed to be enhanced and developed and what kind of design space we were about to enter.

7.2.4 Fiber-winding Experiments

In parallel to the final robot development, material tests were conducted in order to test different fibers and resins to be used for the first large-

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[13] Firgelli, P16-P Linear Actuator with Feedback

[14] Maxon, 139885, Geared DC motor

[15] Uxcell, PN: A14010700ux0271, 3x3 mm Solenoid air/gas valve

[16] Uxcell, Micro gear motors, 15RPM

[17] Arduino Pro Mini, 3.3v, Microcontroller

[18] SparkFun, PN: DEV-09627, Pro Mini FET Shield

[19] SparkFun, PN: LSM9DS1, 9DOF IMU Breakout board

[20] Actuonix, PN: LAC, Firgelli Linear Actuator Control Board

scale demonstration of a multi-robot system.

7.2.4.1 The Winding Rig: Material variation/experiments

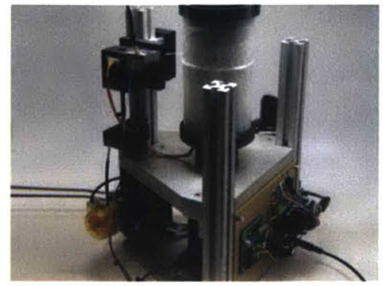

Figure 7.19: Stationary winding rig, made in collaboration with Nassia Inglessis. Image: Nassia Inglessis, Mediated Matter

A stationary experimental winding rig was developed (Figure 7.19), providing a platform with which to test various fiber yarns, resins and experiment with wind patterns. The rig was also used to test individual components and mechanisms later applied to the robot design. Multiple single segment wind patterns were explored as shown in Figures 7.21 and 7.22, in order to find suitable linear and rotary velocity configurations to be implemented in code in the first large-scale construction using the robots. The limiting factor for overall speed and a suitable crosswind pattern formation was the linear drive speed, given the compact robot design and thus space constraints for motor choice, which in turn limited torque in relation to velocity. In fiber winding, the angle of the fiber crossing at each rotation is critical for structural performance of individual fiber wound tubes. However, as we also wanted to achieve a reasonable overall build speed performance of the system, we had to find a compromise between overall structural strength and time required for construction. We also tested the winding thickness required for overall strength in relation to overall height of individual tubular members. Further, the rig provided basic insights for the sequential segment connection strategy and overlap as illustrated in Figure 7.20.

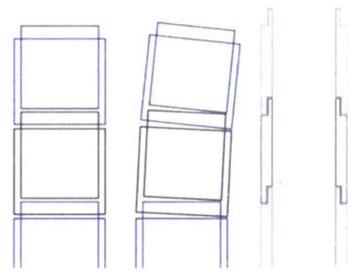

Figure 7.20: Segment overlap strategy with an off-set lower and top winding layer. In collaboration with Nassia Inglessis, Mediated Matter.

7.2.4.2 Single Tube Overlap & Connecting Strategy of Segments

Figure 7.21: Layered cross-wind with matching overlap, creating a lattice. Image: Nassia Inglessis.

Initially, the overlap from segment to segment created bulging areas, which created problems especially in curved areas as these thicker areas interfered with the rotary winding arm. So the previously mentioned connection strategy enabled a more consistent wall thickness and outer diameter over the length of the tubular members. Even though this building strategy worked for a self-supportive structure in the first large-scale implementation of the system, there are more ideas on how to make these tubular members much more robust in carrying loads for future implementation. One of these strategies could include applying fiber across the length of the tube, as this would significantly increase the bending performance of the tubular members when tensile forces are applied. Over the length of individual segments the robot could in its current state (form) apply the fiber yarn almost vertically across its length sequentially with more horizontal winds in relation to the tube's length fixating the vertical ones. A probable weak point remains at the overlap of individual segments; this could only be overcome by additional development of a secondary fiber feed system laying down fiber across the length of the columns. It may be feasible to carry this fiber onboard the robot as it only needs to come in the overall length of the column in order to provide some additional strength in bending.

Figure 7.22: Sample with tight overlapping weave pattern and decrease resin saturation for the last layer, image Nassia Inglessis.

7.3 Agent: Individual (Single) Robot Design

7.3.1 Introduction

A single robot (Figure 7.23) consists of a fiber winding arm moving vertically up and down while spinning around its vertical axis. A tubular silicone inflatable membrane sitting at the outer wall of the robot body, which is inflated while winding and deflated for demolding (detach the fiber/resin tube from the robot's body after one winding sequence), enabling the robot to move freely up from within the tube. A small onboard air pump and solenoid valves provide in/deflation of the membrane. The upward movement is actuated by an eight-motor-drive-assembly at the bottom of the robot using four encoders for position tracking and orientation trajectory. An inertial measurement unit (IMU) provides information about the positioning of the robot and—in the future—could be used to record trajectory data for inter-robotic communication. Resin and fibers are fed up to the robot through an initial foundation base running up through the tube the robot makes. At the top of the robot is a fluid rotary transmission feeding the resin to the outside of the winding arm and wetting the fiber with resin at the tip/nozzle, right before application to the inflatable silicone membrane. A slip ring assembly provides electrical rotary transmission for rotary and linear limit switches as well as future sensing devices attached to the outside winding arm. UV LEDs are sandwiched between the robot's body and the translucent polycarbonate inner wall of the inflatable assembly for curing the photo-reactive resin. Two stacked circular custom circuit boards sit at the bottom of the robot for easy access, providing Wi-Fi communication with a central computer, IMU, DC and stepper motor drivers and power control and distribution.

Figure 7.23: Final Fiberbot Robot

Figure 7.24: Detail of robot rotary drive assembly, winding arm, linear rail and limit switches.

7.3.1.1 Robot Housing (Body parts)

In order to later batch produce the robots, we decided to go with a 3D printing design approach, giving us the freedom in design to compactly embed all electronics and electromechanical parts seamlessly with a cost-effective way of production allowing for relatively complex body part geometries. In addition, the modularity of all sub-assemblies is critical for maintenance and accessibility in this prototyping stage of the project, which resulted in 20 unique prints as shown in Figure 7.25 and a total of 30 3D printed parts per robot. The first prototypes of this new design were printed using an FDM 3D printer[21], while for the batch production of 20 robots, all 600 3D printed parts were produced in Nylon using a Selective Laser Sintering (SLS) machine[22].

Figure 7.25: Detail bottom view of base drive.

[21] Tiertime, UP BOX, FDM 3D Printer

[22] EOS GmbH, Fine Polyamide PA 2200, printed via Shapeways

List of 3D printed parts:

a. Nozzle Connector, carbon fiber tube to brass nozzle

b. Linear rail hard stop

c. Internal rotary stepper motor wire handler and slip ring shaft

d. Rotary fluid transmission fixture on rotary stepper motor

e. Slip ring brush fixture, linear screw fixture, linear rail fixture, 'sense' PCB for flat flex cable

f. Cover for e. FFC handler

g. Linear stepper motor mount, air pump and solenoid fixtures, rail carriage mount, DC fan, brass fiber guide tube mount, resin tube fixture

h. UV LED curing barrel, polycarbonate tube spacer

i. Top inflatable plug and limit switch PCB fixture

j. Bottom inflatable plug, drive base plug fixture

k. Central core of drive base, spring fixtures, internal plug and wiring fixtures, linear guides for spring-loaded drive wheel 'cartridges'

l. Drive wheel motor cartridges, linear guide elements, motor encoder housing

m. PCB spacer

n. Grooved wheel

o. Bottom plate of drive base, linear guide features and plug fixture to PCB.

p. Drive base cover for cooling fan integration and easy access to the electronics.

Figure 7.26: Robot 3D printed body unique parts

7.3.2 Robot Functions

7.3.2.1 Winding

Two stepper motors are used to actuate the fiber winding function. A linear stepper motor[23] in the robot housing drives a modified hollow shaft rotary stepper motor[24] linearly up and down while the rotary motor spins a winding arm around the central core of the robot. A single linear rail[25], fastened directly to the rotary stepper motor and a rail carriage[26] and mounted to the inner robot housing, assures linear alignment (Figure 7.27).

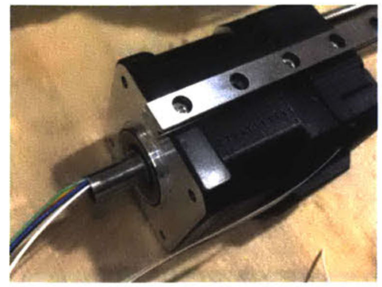
Figure 7.27: Single linear rail directly fastened to the stepper motor.

The Fiberbot linear motion was designed to carry the rotary stepper motor drive assembly. In order to have a smooth and sturdy linear motion I designed a two-rail assembly, which housed the rail carriages inside the robot's body, with two rails attached to the drive assembly. This system used lightweight anodized aluminum rails and Frelon-lined aluminum sleeve carriages[27]. Although this design worked sufficiently, issues of misalignment occurred frequently, putting unnecessary strain on the linear stepper motor. The dry sleeve bearing required a moderate play to minimize friction, and as these were mounted vertically a significant amount of side load was applied during the winding function as the rotary drive assembly extended out of the robot's body.

The solution was to use a significantly heavier rail carriage assembly, which used a stainless-steel rail and ball bearing carriage[28] with minimal play. This stainless-steel ball bearing rail and carriage was sturdy enough to reduce the design to a one rail design which freed up space inside the robot's body and reduced the weight overall. The single-rail design also allowed the rail to be mounted directly to the side of the stepper motor reducing overall of assembly height while maximizing travel distance.

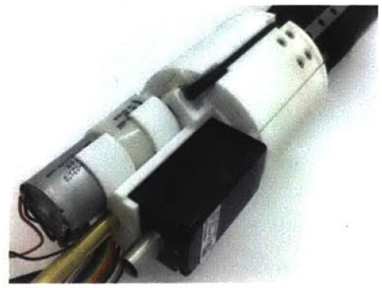
Figure 7.28: Linear non-captive stepper motor lifting the rotary stepper motor.

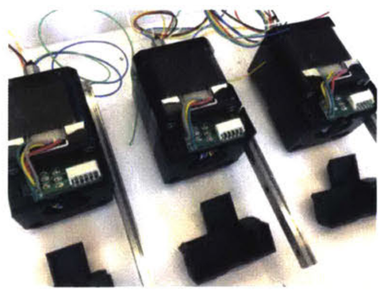
Figure 7.29: Slip ring intergration, PCB wire handling and cover below the rotary stepper motor.

Since the winding function is an open-loop system reliant only on the step and direction signals, linear and rotary limit switches are fixed via a custom circular PCB at the top plane of the robot's body and triggered by a press-fit ball-nose spring plunger[29] on the rotary winding arm (Figure 7.30). An electrical 6-contact slip ring assembly[30] is located at

[23]Nanotec GmbH, L2818L0604-T5X5 Stepper Motor and ZST5-2-200-1 Screw

[24]RobotDigg, PN: 17HS3001-70N Stepper Motor

[25]McMaster-Carr, PN: 6725K33, Guide Rail

[26]McMaster-Carr, PN: 8438K2, Ball Bearing Carriage

[27]McMaster, PN: 9880K5, Frelon Sleeve Bearing Carriage and 7 mm Wide Rail, 160 Lb. Static Load Capacity

[28]McMaster Carr, PN: 8438K2, Corrosion-Resistant Ball Bearing Carriage and Stainless-Steel Rail

[29]McMaster-Carr, PN: 8262A21, Ball Nose Spring Plunger

[30]Moflon, PN: MSP 106, Through-bore Slip Ring

the bottom of the rotary drive assembly transferring a single contact to the outer arms ball-nose spring plunger limit switch and provide additional 5 contacts reserved for future sensing applications not yet implemented[31].

A small PCB routes the wires of the slip ring assembly and the rotary stepper motor to a Flat Flex Cable (FFC) attached to A) the rotary drive assembly moving linearly up and down, and B) to the main body of the robot.

Figure 7.30: Winding arm, a.) fiber tensioner, b.) ball-nose spring plunger making contact with limit switch PCB.

7.3.2.2 Material Feed—From Backend to Nozzle

When considering a fabrication robot, the material feed is one of the most critical parts of this system. Especially in an attempt to reach large-scale implementation of the robotic system, besides the challenges in locomotion and orientation and the batch production of multiple robots, how the material was supplied and applied provided multiple challenges such as friction build-up in fiber feed as well as pumping viscous and sticky liquids over long distances in a compact form factor.

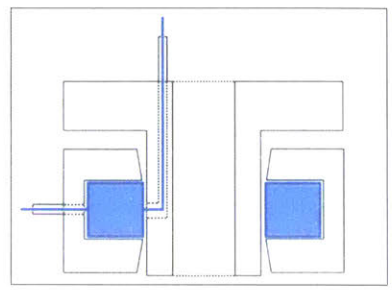

Figure 7.31: Diagram of fluid rotary transmission (FRT) design.

7.3.2.3 Robot Material Handling

The material feed for the robot is designed such that the material is brought up to the robot through the fiber composite tube it produces, centrally through the robot to the outside of the winding arm and out the nozzle to be applied on the outside of the structure. This approach bears several design challenges, as the fiber material is continuous and prone to tangling in a rotating winding system, while the viscous fluid handling of the resin in a continuous winding motion requires a custom designed fluid rotary transmission (FRT). The custom design of the FRT (Figure 7.31 and 7.32) is mainly necessary due to the tight space constraints of the robot as well as the large hollow central core required for the central fiber feed. In common fiber-winding application the mandrel is spinning while the material (fiber and resin) is stationary. In the robot this system is inversed, as the robot is itself the mold and thus requires the material to be in motion. The robot's central core is hollow for the fiber to freely move from the bottom inlet to the top outlet. Through the central core of the stepper motor, slip ring and FRT, wires are fed up via a nylon spacer leaving a central 2 mm hole for the fiber feed in the rotary drive assembly, exiting the winding arm at the top. The fiber then is threaded through a spring-loaded tensioner mounted to the top of the winding arm, a guide hole on the winding arm and back down next to the carbon fiber tube holding the nozzle. The fiber then enters the nozzle from the back, where it is wetted with resin, exits the nozzle fully wetted, and is wound around the robot's inflatable body.

Figure 7.32: Final fluid rotary transmission (FRT). A flanged brass internal rotary shaft with internal liquid channel and aluminum housing with two press-fit fluoro spring loaded seals.

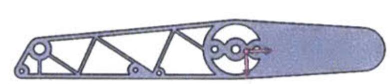

Figure 7.33: Winding arms center of mass (offset from center is necessary as of additional components on the long side of the arm) Image: Sara Falcone

At the robot, the resin tube connects to a custom expandable silicone tube design, to allow for the reciprocating motion of the rotary drive assembly. The braided design of multiple expanding silicone tubes

[31] Future applications and developments are discussed in section 7.11.2

became necessary after several fatigue failures of single silicone bands. From this expandable tube design the resin is fed into a custom-built fluid rotary transmission (FRT) in order to deliver resin to the outside of the revolving winding arm. The custom FRT is designed to robustly transfer resin through a fixed but linearly moving inlet to the rationally moving outlet. The FRT is made from an aluminum outer ring holding two press-fit fluoro rubber seals at the top and bottom and a barbed nylon inlet connector and a hollow flanged brass shaft press fit onto the direct drive rotary stepper motor. Internal to the hollow shaft's wall is an L channel with an outlet at the top of the flange bringing resin from the internal chamber to the outside of the rotating arm as described in Figure 7.31. Upon exiting the rotary fluid transmission, the resin is fed through another silicone tube across the winding arm and down to the nozzle outlet.


Figure 7.34: Final nozzle design. The fiber is wetted inside the nozzle right before application to the mandrel.

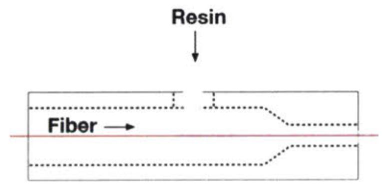

Figure 7.35: Diagram of the nozzles, resin and fiber flow.


Figure 7.36: UV-curing LED assembly.


Figure 7.37: Robot inner architecture. linear stepper motor, DC air pump, solenoid valves, DC cooling fan.

The design development of the FRT was challenging, as it had to be smaller than most FRTs regularly available on the market, while having a hollow shaft to be press-fit directly onto the stepper motor. It also had to be cost efficient due to the number of robots we wanted to build, and function robustly, as any leakage would flow straight into the rotary stepper motor with detrimental effect. Another major concern was friction build up as the direct stepper drive would be limited in its winding speed by any applied friction through the slip ring, with FRT as well as friction of the fiber feed increasing over the span of the overall robotically fabricated structure height. The final design was also the simplest, as it used the stepper motor and a 3D-printed casing for the outer aluminum housing to align the shaft and seals minimizing overall height, as no additional bearings were required. The spring-loaded double lip seals[32] had low alignment tolerance unlike the PTFE seals used in previous tests and robustly transported the resin from internally to the outside rotary winding arm.

The winding arm assembly consists of a counter-balanced horizontal arm attached to the press-fit shaft extension of the rotary fluid transmission of the rotary stepper motor direct drive. The rotary winding arm was designed iteratively, reducing weight and (almost) eliminating centrifugal forces arising from the arms' inertia while spinning. Weight was reduced by triangulated cut outs using a water jet and 6.35 mm aluminum sheet stock. Initial prototypes proved to be sufficiently stiff as the arm was pulling the fiber, however, centrifugal forces still created a 'wobble' of the main robot body. By calculating the center of mass of the arm, including the carbon fiber extended tube and brass nozzle, we could reduce the imbalance to a minimum. As can be seen in Figure 7.33 we added a solid aluminum pat to the back of the winding arms design, while maintaining the lightweight triangulated arm configuration at the front from previous iterations.

A lightweight carbon fiber tube is press-fit into the aluminum part where

[32] Motion Industries, PN: 01294503, SKF Sealing Solutions 6139, Fluoro Rubber Oil Seal, CRWA1 design.

the brass nozzle is attached using a nylon t-connection part. The nozzle is designed to let resin flow into its center and has a larger 2 mm bore opening to the fiber inlet and is tapered towards the smaller 1 mm outlet. The resin is wetting the fiber only inside the nozzle keeping friction build-up of the fiber feed up to the robot's nozzle at a minimum. The final nozzle combined all functionalities (discussed in the previous section) in a very simple and compact form factor. A 3 mm diameter brass rod was turned with a 2 mm fiber inlet and a 1 mm fiber outlet. This through-hole was chamfered internally in order to create a smooth and easy to thread fiber guide. A resin inlet hole of 2 mm was drilled, centrally and perpendicular to the length of the nozzle. On departure of the small outlet the fiber is stripped of excess resin. The nozzle needs to be sufficiently polished such that the fiber will not break around sharp corners entering and exiting the nozzle. A nylon 3D printed housing connects a carbon fiber (CF) tube and the nozzle perpendicular to one another. The resin is delivered through the CF tube wetting the fiber right before application to the robots mandrel.

Figure 7.38: Fabrication of the two silicone sleeves before assembly.

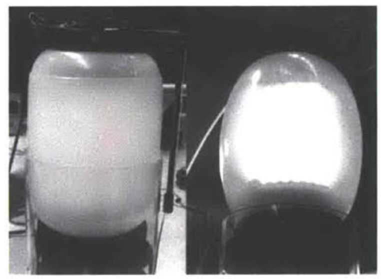

Figure 7.39: Left: Inflatable with secondary sleeve, right: Inflatable with single sleeve.

7.3.2.4 On-board Curing

The system is designed to operate continuously and while sunlight provides plenty of UV radiation to cure the resin used here, the robot also has a curing system in place for nighttime construction. A 405 nm UV LED strip[33] is wrapped helically around the main body, which is encased in a clear polycarbonate tube that acts as the inner wall of the inflatable membrane, though which it cures the resin from the inside.

Figure 7.40: Robot base drive.

7.3.2.5 Inflatable system

The inflatable mandrel (outer body of the robot) is key for molding and de-molding the fiber composite material as well as enabling locomotion of the robot within the tubular structure it fabricates. A 6v DC air pump[34] and two small normally closed solenoid air valves[35] are used for inflation and deflation of the silicone membrane. The inflatable membrane consists of a dual layer silicone sleeve of which the inner sleeve acts as the main inflatable membrane and is plugged at the top and bottom to the polycarbonate tube. The shorter 100 mm silicone sleeve acts in shaping the former sleeve from a bloated shape to a more cylindrical shape. Since the inflatable membrane acts as the mold for the fiber-wound tubular members a consistent outer diameter is achievable for making the tubular structures. Not only is the tube's diametrically consistent geometry important in terms of structural considerations but also for the robot's drive function as it progresses forward inside the tube it builds.

Figure 7.41: The two PCBs are stacked underneath the base drive.

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[33] Wit-Lighting, UV 395nm-405nm, 3528 SMD LED Flex Strip Light, IP20, 12V DC

[34] Uxcell, PN: A17042000ux0808, Mini Air Pump Motor, DC 6V, 68 mm L x 27 mm D x 27 mm W

[35] Uxcell, PN A14010700UX0271, 5V DC Solenoid Electromagnet Valve

7.3.2.6 Drive (Locomotion)

The drive of the robot uses an assembly of nylon 3d printed parts, consisting of an inner core and two plates at the top and bottom, with integrated linear guide features for four spring-loaded 'drive cartridges' holding eight DC gear motors[36]. Each cartridge has two motors and two U-grooved wheels with rubber belts[37] pressing against the inner wall of the built tubes with good grip, minimizing slippage.

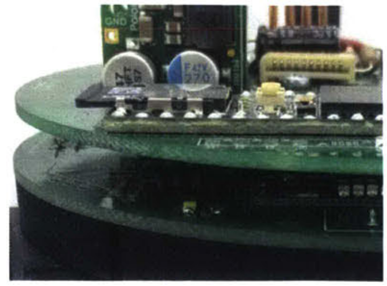

Figure 7.42: Detail of the two custom PCB's.

7.3.2.7 Orientation

To achieve curved tubular structures the robot orients itself in 3D space according to the IMU reading and the four-encoder readings of the drive motors after each winding sequence. The motors drive forward or backward depending on required orientation. The spring-loaded wheel cartridges can tilt and conform to the inner wall of the tube for angles up to 3 degrees, before the upper and lower plates make contact with the walls.

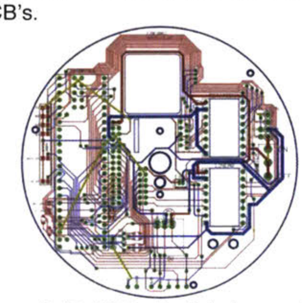

Figure 7.43: PCB 'Brain', Image Levi Cai, Mediated Matter.

7.3.2.8 Electronics

The robot's electronics consist of two circular custom PCB's which are populated with the following list of parts:

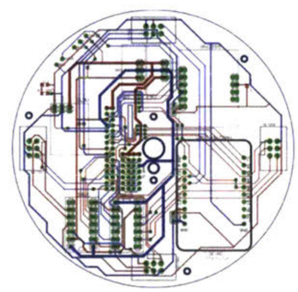

Figure 7.44: PCB 'Pinky', Image Levi Cai, Mediated Matter.

ITEM	PART #	#	VENDOR
12V 2.2A Switching Reg.	2855	1	Pololu
6V 2.5A Switching Reg.	2859	1	Pololu
5V 500mA Switching Reg.	2843	1	Pololu
3.3V 1A Switching Reg.	2830	1	Pololu
3.3V 1A Switching Reg.	945-2409-5-ND	1	Digikey
DRV8880 Stepper Driver	2971	1	Pololu
DRV8825 Stepper Driver	2977	2	Pololu
DRV8835 DC Motor Driver	2135	2	Pololu
Teensy 3.6	1568-1442-ND	1	Digikey
Adafruit HUZZAH ESP8266	1528-1223-ND	1	Digikey
Adafruit BNO055 Breakout	1528-1426-ND	1	Digikey
MOSFET 2N 30V, TSMT5	QS5K2CT-ND	2	Digikey
100uF, 35V, Alum. Cap.	493-5925-3-ND	3	Digikey
100uF, 6.3V, Ceram. Cap.	493-5925-1-ND	2	Digikey
33uF, 50V, alum. Capacitor	P5184-ND	2	Digikey
0.1uF, SMT Cap.	311-1361-1-ND	2	Digikey
Molex Nanofit RCPT 4CKT	WM14969-ND	1	Digikey
Molex Nanofit 4CKT	WM14969-ND	1	Digikey

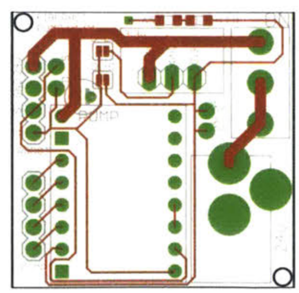

Figure 7.45: Base PCB 'Pump Board', Image Levi Cai, Mediated Matter.

[36] BringSmart, JGA12-N20 6V 41RPM

[37] McMaster, PN94115K219, Neoprene O-Ring

Molex Nanofit crimp term.	WM14956CT-ND	4	Digikey
Molex FFC 10pin Connector	WM11038-ND	2	Digikey
Parlex FFC 10pin Cable	HF10U-18-ND	1	Digikey
2 mm Header Recept. 30pin	ED4264-30-ND	1	Digikey
2 mm Header Recept.14pin	S5750-07-ND	2	Digikey
2 mm Header Pins (60)	S5801-30-ND	1	Digikey
Slide Switch 6A 125V	360-2385-ND	1	Digikey
LED Green Clear 0805 SMD	732-4986-1-ND	1	Digikey
LED SMT 0805	492-1331-1-ND	2	Digikey
Resistor 65ohm SMT 0805	311-64.9CRCT-ND	2	Digikey
Power Jack	CP-002AH-ND	1	Digikey
Base Fan	603-1839-ND	1	Digikey
Inner Fan	259-1559-ND	1	Digikey
Diode Schottky SMT	DB2J40700LCT-ND	2	Digikey
PCB Brain	Custom	1	PCB-WAY
PCB Drive	Custom	1	PCB-WAY

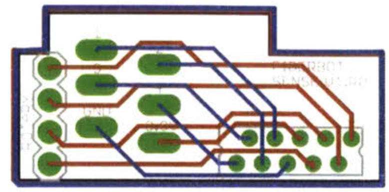

Figure 7.46: PCB 'Sense'. Image: Levi Cai, Mediated Matter.

The two circular PCB's are populated with the listed boards and components, separating the ground planes of the high-power components such as the stepper drivers and the LEDs from the more sensitive components such the IMU sensors and microcontroller. The two PCBs simply connect via a two row, 2 mm header pins and socket interface and a two-row, 2 mm header pin and socket interface to the base of the robot drive. Two screws hold the two PCBs, separated by a spacer, fixed to the base plate. A perforated cover and fan assembly cools the heat sinks on the stepper driver boards and protects the circuitry from any material spillage and impact. The 'Pump Board' PCB acts as the power IN for the whole system at the base foundation and also incorporates the stepper motor driver for the resin pump. The 'sense' PCB is located inside the rotary drive assembly routing wires of the slip ring, stepper motor and combining them in the FFC cable connector to the rest of the robot.

7.3.2.9 Backend Material Feed

The backend system is designed to combine the built structure's foundation (bases) and backend material feed system. Each base consists of four steel tubes, 110 mm in diameter (same as the fiber composite tubes the robot makes) resting and being held together in a triangular configuration by water jet steel braces. Each base is fixed to the ground by six 50 cm long, 12.5 mm square ground pins.

Figure 7.47: Foundation bases with integrated resin supply feed system.

The material feed system starts with the material itself—fiber and matrix (resin). I will describe in detail the material feed system for materials used specifically in this proof-of-concept structure. I will expand on the potential of using other materials with the same or very similar system in a later section of this chapter.
The fiber used here is a fiberglass yarn[38] in combination with a photopolymer[39]. The fiber comes in 8.26 kg bobbins with a total fiber

[38] Vetrotex, EC13 300 Z20 TD37C

yarn length of 27,000 m. As the fiber yarn bobbins are too heavy and large to be carried on board the robot they are placed next to the custom steel bases on the ground while fabricating. The yarn is fed through a small hole to the inside of the base and up centrally through the robotically fabricated tube to the robot.

Figure 7.48: Resin bottle with wires and tube helically wrapped in nylon sleeve.

The resin supply chain consists of a UV resistant bottle filled with resin, integrated into the bases of the system for ease of access and refilling. A customized stepper motor peristaltic pump[40], which sits below the resin container, delivers resin through a nylon tube to the robot. A 7 m tube and three electrical wires are bundled inside a nylon wire sleeve and wound around the resin bottle inside the base in order to helically unwind inside the bases as the robot is building its structure. This tube-wire assembly provides the robot with power and also sends signals back to the resin pump for precise start/stop and output quantity of the resin.

Figure 7.49: Detail of resin pump, tube wire assembly, PCB fan.

7.3.2.10 Power Handling

The robot is powered by a 120v AC to 24v DC, 4 Ah, power adapter housed inside the hollow core of the fiber bobbin. The power adapter is plugged into the pump board PCB via a barrel plug, which distributed the 24v DC to the stepper motors of the base pump, and the two onboard stepper motors directly and the switching regulators supplying 3.3v DC, 6v DC and 12v DC respectively to the driver and microcontroller logic, solenoids and fans and the air pump and LEDs.

Figure 7.50: Power IN at the base supplying the robot through 7-10 m cable.

7.3.2.11 Code/Control

The control code is written in C/C++ and is run in the Arduino IDE. The basic structure of the code is segmented into cases, which are called in the main loop in sequence or on demand. The basic cases are as follows:

(O) Orient
(I) Inflate
(W) Wind
(LM) Linear Motor Drive
(RM) Rotary Motor Drive
(D) Deflate
(L) UV LED (on/off)
(Q) Stop

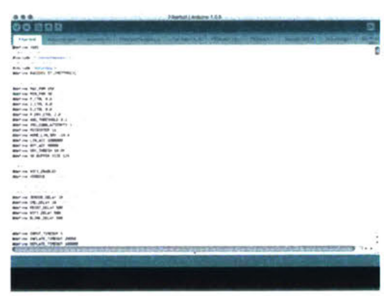

Figure 7.51: Arduino IDE running the Fiberbot code

The initial software for previous prototypes was developed in collaboration with Jorge Duro and Levi Cai, while the final code for this final iteration of the robot was developed mainly by Levi Cai and thus will not be discussed here in depth.

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[39] Solarez, Vinyl Ester Epoxy Resin

[40] Kamoer Fluid Tec, PN: KAS-S 10 SE 6, Peristaltic Pump

7.3.2.12 Control Interface

A control interface was also developed by Levi Cai in order to load instruction data and send it via Wi-Fi to the individual robots. For the purpose of the large-scale experiment it was important to also be able to interact with individual robots while construction was underway as errors occurred. This simple interface allowed us to interact with individual robots while other robots were following instructions simultaneously.

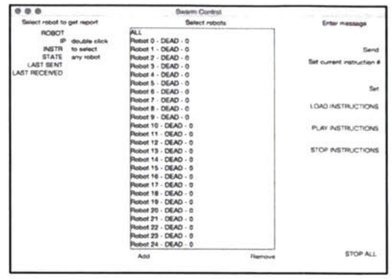

Figure 7.52: Fiberbot interface 'Swarm GUI' developed by Levi Cai

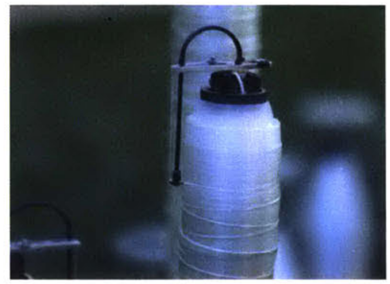

Figure 7.53: Fiberbot winding fiber, constructing a tubular member while deflating its silicone membrane.

7.4 Material System for the Fiber Bot

7.4.1 Material Approach

The Fiberbot is 'fed' with fiber and resin through the column it makes. At its base (foundation) sits a spool of fiber and a resin container. Resin is pumped through a small tube (nylon tube, 3 mm OD, 1.5 mm ID) in the length of the maximum distance of the expected tubular member. For the final demonstration of this robotic system, Vetrotex glass fiber yarn (EC13 300 Z20 TD37C) and Solarez Vinyl Ester Epoxy Resin was used for winding the tubular members. One spool of this specific yarn holds 27 kilometers, providing fiber material for a column 11.93 meters in length without replenishing the material feed stock and requiring an estimated 4.5 liters of resin. However, depending on curvature of the tubular members there may be limitations such as friction build up of the fiber running on the inner walls of the tubular members as well as pressure loss over such long distances in the resin feed tube. It was shown that 4.5-meter tubular members are feasible in building large-scale structures. In theory the material can be replenished while the robot is building the structure, providing continuous operation over longer distances, however, this may require an additional fiber pulling mechanism to reduce the strain on the winding function as well as a more sophisticated resin supply system, potentially adding an on-board micro-dosing pump with a secondary feeding pump providing sufficient pressure over longer distances.

7.4.2 Material Cost of Single Tubular Member (1m) Built by a Single Fiber Bot

The Fiberbot builds its tubular structure segments in sequences of 60 mm long and 110 mm in diameter. The fiber is deposited on the inflated membrane, requiring 345.6 mm (circumference) of fiber for a single revolution of the winding arm. Accordingly, 135.8 m of fiber are required at 393 revolutions, per 60 mm built segment. For a 1 m tubular member, 16.66 segments and 2262.42 m of fiber are required. The cost of the specific *Vetrotex* glass fiber currently in use is $29.27 per 27000m/spool and thus $2.45 per 1 m (110 mm diameter) tubular member constructed by the Fiberbot.

22.7 ml of resin is used per 60 mm segment and 378.18 ml for a 1 m tubular member. At a cost of $0.021 per ml, the cost per meter is $3.84. The total material cost (glass fiber yarn and resin) of a 1 mtubular member 85 mm in diameter is $6.29.

Depending on quantity these numbers may vary and different fibers will also have very different price points. However, this cost discussion for a known and tested material helps to estimate overall construction costs for an architectural deployment of the system.

Robotic fiber winding around inflatable membrane
Fiber length/revolution = (**π** x 110 mm diameter inflatable membrane) = circumference = 345.6 mm
Fiber length/60 mm segment = (345.6 mm fiber length/revolution x 393 revolutions/segment) = 135.8 m
Fiber length/1-meter tubular member = (135.8 m fiber length per segment x 16.66 segments = 2262.42 m

Fiber
Fiber cost/meter = $0.001085
Fiber cost/60 mm segment = (135.8 fiber length/segment x $0.001085) = $0.15
Fiber cost/1-meter tubular member = (2262.42 m fiber length/1 m tubular member x $0.001085) = $2.45

Resin
Resin cost/ml: $0.021
Resin cost/segment = (22.7 ml x $0.021) = $0.48
Resin cost/1 m tubular member (22.7 ml x 16.66 segments) = $3.84

<u>Total material cost for a 1-meter tubular member (Fiber $2.45 + Resin $3.84) = $ 6.29</u>

Build Speed of Single Tubular Member (1 m) Built by a Single Fiberbot

An important factor to consider is the build speed. Currently, the Fiberbot takes 3 minutes and 56 seconds for one winding sequence of 60 mm in height and 110 mm in diameter, with the winding arm rotating at 1.667 revolutions per second. Curing time of the resin is about 5 minutes but is not considered as de-molding is already done during the end of the winding sequence. Drive-up and orientation takes 10 seconds and inflation takes 21 seconds, totaling a sequence build time of 4 min and 27 seconds. With some variable orientation time in the drive-up sequence and under ideal conditions an estimated 1 hour and 15 minutes build time is required for the robot to complete a 1 m tubular member. These numbers are taken from the latest version of the Fiberbot and the build time compared to its predecessor was almost cut into half from 2 h and 24 min to 1 h and 15 min.

1.667 revolutions per second for winding arm
3:56 min per 393-revolutions/winding 60 mm segment
0:30 min drive-up and orientation
0:21 inflation

4:27 min total time for 60 mm Segment
<u>Total time for a 1 m tubular member (16.66 segments x 4:27 min/segment) = 1:15 hours</u>

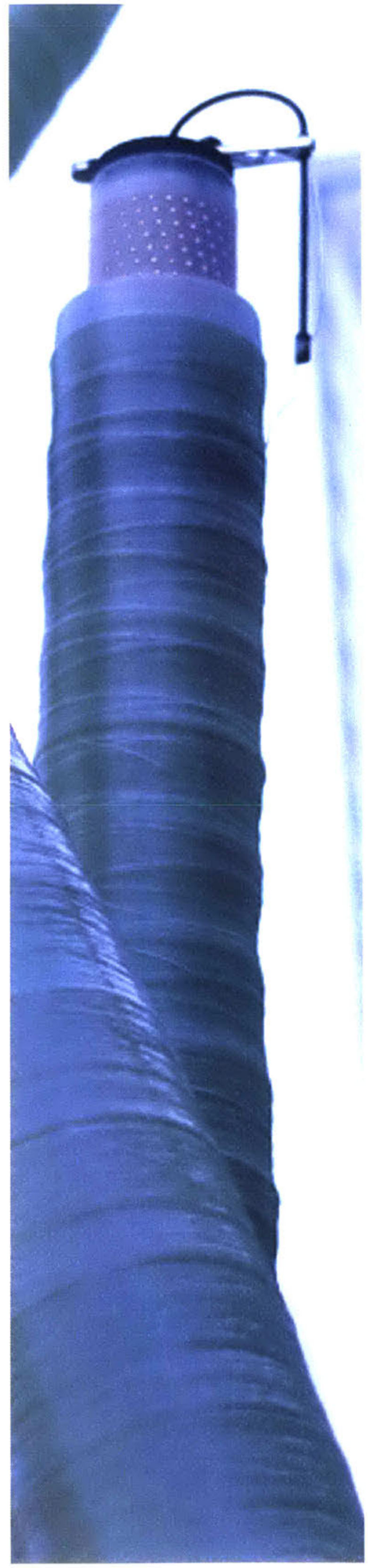

Figure 7.54: Fiberbot making a tube.

7.5 Agency: Final Large-scale Structure

A large-scale structure of 4.5m in height was constructed using 16 robots over a period of 48 hours. In Figure 7.71 and 7.72 the final large-scale structure is shown and Figure 7.83 (end of chapter) shows a sequence of construction.

Each column varies its material gradually in thickness and across its height. As will be discussed in the section on design strategies of the system, each column is built with a different geometry; the design strategy may include multiple layers of variation in fiber deposition and distribution in accordance with its structural geometric properties. However, for the design of this proof-of-concept structure we decided to only implement one wind pattern for all columns and include only one mode of grading material properties along each columns length. In the following, the first fully automated construction by 16 robots will be discussed.

To scale a robotic system from 3 working robots to 20 working robots provides a challenge in itself. As a designer of processes, I am used to building and working with prototypes and I am also used to things breaking and errors occurring, and fixing them and debugging on the fly. However, when dealing with a batch production of 20 robot prototypes, the clear aim is to avoid any failure as debugging on the fly is just not possible, hence the system needed to be as robust as possible in order to fabricate with multiple robots at the same time.

The fabrication of 20 robots (Figure 7.55) was done in-house at the Mediated Matter group workspace, including the soldering of 40+ PCBs populated with 1000+ parts and boards, wiring and assembly of 40 stepper motors, 20 air pumps, 40 solenoid valves, 180 springs, 180 DC encoder motors and 600 3D printed mechanical and housing parts to name but a few. Custom fabricated parts such as the aluminum wind arm were water jet cut; brass nozzles and rotary fluid transmission were turned; linear drive screw, spring-loaded ball plunger and CF tube press-fit; and the silicone inflatable membrane was cut and joined, among many more parts being customized, drilled, tapped and fastened.

7.6 Mapping the Design Space: A Case for a Woven Architecture

The Fiber Bot project serves as a first-of-its-kind demonstration for achieving both material tunability and a distributed robotic fabrication system, *on the large scale*. Each member is designed and constructed as a solitary member, much like a thread within a woven fabric. No direct rigid connections are made between individual strands; however, the strands may support each other under self-bearing load (*e.g.* increasing height of structure) or external forces (*e.g.* wind). The core idea is to construct by weaving (globally) instead of stacking, with the potential to create novel flexible architectural forms. Stacking blocks of the same material together leaves very little room for material tailorability, defined as variation in material density and the potential integration of added functionality such as light guides or resistive

Figure 7.55: 20 assembled Fiberbots.

Figure 7.56: DC encoder gear motors being wired.

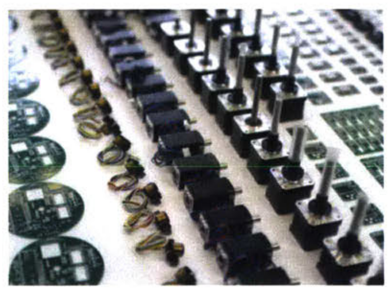

Figure 7.57: Parts ready for assembly.

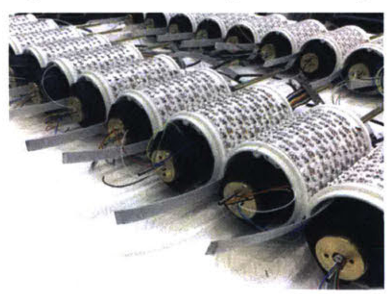

Figure 7.58: Assembly of robot inner body and rotary drive assembly.

Figure 7.59: Gluing silicone sleeves.

heating/electrical transmission via metallic fibers. Also, shapes (3D forms) are relatively limited within a rectangular block system. However, building solely from fiber composite tubes may be limiting too as there are also margins in resolution and possible shapes. The proposed building method provides an alternative to existing approaches; and while it is about achieving a self-supporting architectural scale structure via a distributed robotic system, it is as much about trying to do so via a hierarchical method of weaving (Figure 7.60), without the need to connect individual members in order to create a more flexible materially-tuned building skin.

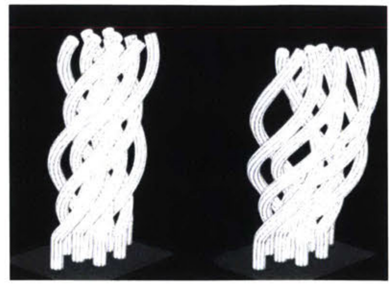

Figure 7.60: Simulation of tubular members' deformation under gravity, leaning on each other, simulation done by Cristoph Bader.

7.6.1 Fiber and Matrix—Scales of Material Tunability

The material strategy for the distributed construction system deals with the combination of stiff individual tubes locally supporting themselves, but also acting as 'flexible' strands in a global fabric of the overall structure. The idea is to deploy the 'best of both worlds'—the self-supporting structural integrity of a solid locally, with the flexibility and elasticity of a woven fabric globally. The goal is to create a hierarchical system operating across multiple scales with performance value on the global structure (Figure 7.61). First, consider the material scale, where individual robots are deployed using different fibers and resins according to the function in the larger system. Second, consider the scale associated with fiber distribution, where the winding can be precisely controlled to achieve stiffness gradients, from very rigid to spring-like properties through the winding geometry in reference to conventional computer-controlled fiber reinforced composite tubular winding (Mertiny, Ellyin, and Hothan 2004). And third, consider the global geometry of each individual strand's geometry within the network of strands—the woven global structure, determining which strand will lean onto its neighboring strand, greatly effecting structural performance globally.

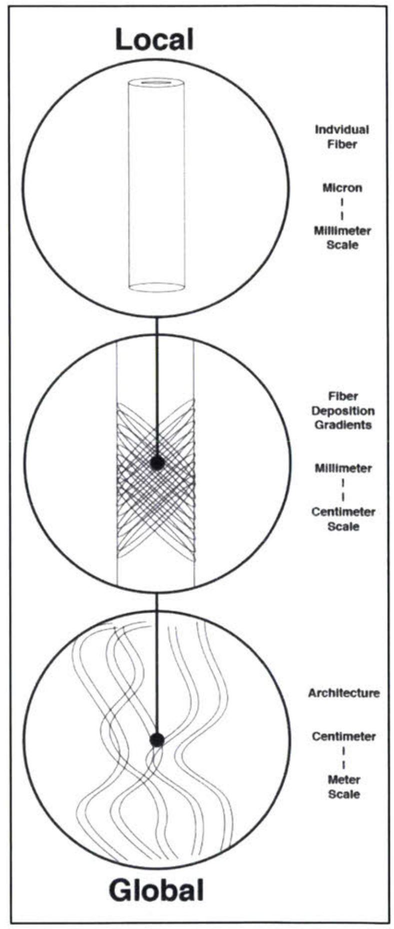

Figure 7.61: Hierarchical process from local to global. Multiple scales in the fabrication process need to be considered—locally, the design of the actual fiber and its capabilities, through to the path of a single fiber through to gradients in the fiber deposition up to the global shape of the architectural structure.

7.6.1.1 Physical Design Constraints

These robots are not designed to create tight connections between individual tubular members, since the rotating fiber winding arm dictates the minimum distance between one robot and another. Although there is a minimum distance between the individual members, the goal is for the entire structure could 'sag' in a controlled fashion, creating contact points to support and distribute the load of each other's weight without the need for direct connection. The overall curve radius of a single tubular member is 114.6 cm, which is determined by the maximum angle of 3° the Fiberbot can tilt when moving upwards after a winding sequence.

The rotary and linear motion of the robot's winding arms create a natural design constraint as it dictates the minimal distance between robots while constructing. Figure 1.62 illustrates the constraint envelope, which has to be considered for the design of a multi-robot structure. The envelope surrounding the robot needs to be no less than 200 mm in diameter and 250 mm in length, starting at the end of the fabricated tube the robot sits in. This constraint only applies to a single robot and its neighboring tube when the robots are started in sequence and will never meet one another directly; however path planning sequentially has to be carefully tuned such that collisions can be avoided. In the case that this cannot be ruled out, which is likely depending on structure scale, this envelope minimal distance constraint applies to all robots, meaning that the minimum distance between tubes is 200 mm from the outside diameter, edge to edge.

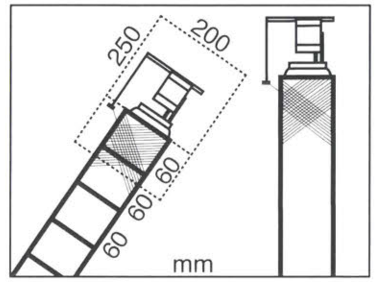

Figure 7.62: The robots cylindrical constraints envelope of 200 mm by 250 mm. Segment length is 60 mm.

7.6.2 Design of Structure and Algorithmic-based Iterations

Several iterations on the design of the structure were done. A computational generative swarm-based design workflow was developed by Christoph Bader from The Mediated Matter group. In this workflow designs could be tested and visually verified in several iterations and strategies. Basic strategies included flocking, mapping and obstacle avoidance. While most simulation included the basics of flocking, of separation, alignment and cohesion in order to assure that the physical constrains of the robotic systems were met as well as to create the helically wound structures and have all robots moving coherently towards an overall 'connectivity' or bundling. As illustrated in Figure 7.63 several design strategies were tested in simulation mimicking potential sensing capabilities of the robot and the design of the structure.

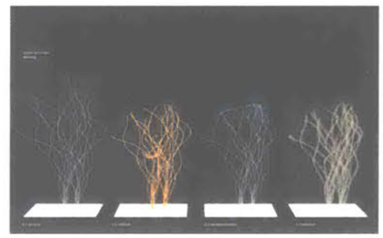

Figure 7.63: Computational simulation of design strategies of sensing, collision, communication and direction. Simulation and image: Christoph Bader, Mediated Matter.

Structural simulations of the columns winding around each other result in expected bending overall. As shown in Figure 7.64, tubular structures wind helically around a single straight tubular member, creating a support system of varying strength. The tight winding of these simulations is unrealistic in the current system, due to the constraints established previously, but conceptually it demonstrates the idea of a global support system within the multi-column structure.

Figure 7.64: Simulation of structural support strategies for columns in a global 'weave'. Image: Christoph Bader, Mediated Matter.

7.6.3 Path Trajectory Design and Implementation

The basic data instructions sent to each robot at each segment are the orientation data of pitch, roll and yaw, the distance of overall travel for the base drive, the winding function for direction and steps in a given time for linear and rotary stepper motors, and the pump motor's time and speed. After each segment, the robot asks for instructions, which are then send from the central computer to the robot.

7.7 Final Installation at the MIT Media Lab

Having established all design constraints, the generative design approach developed by Christoph Bader produced the design for our first large-scale deployment of the system. The first large-scale structure erected by 16 robots was built in front of the MIT Media Lab (E15).

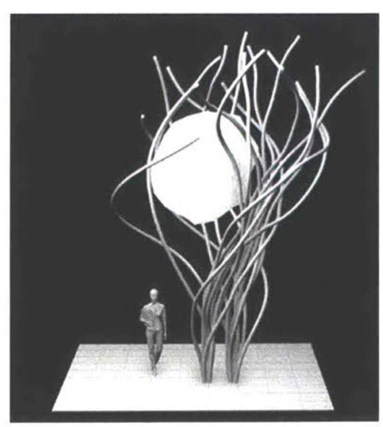

Figure 7.65: Obstacle avoidance design strategy. Image: Christoph

The structural bases holding the resulting overall structure of the installation were made from 110 mm diameter steel tubes, designed to house the resin material feed system. For the installation, four of these tubular bases were connected to form four bases for the 16-robot

deployment. Each of the four bases was connected by a water jet steel triangular base brace.
A jig was made in order to position the four bases in accordance to the CAD file to be fabricated by the robots as seen in Figure 7.66. All robots needed to be calibrated on site, fixing their 'north' position, as we used a relative positioning mode of the IMU because we had significant drift while using the global compass (magnetometer sensor) in the environment of this installation.

This installation was built over the course of two days (Figure 7.68 and 7.69) and resulted in a loosely wound overall structure composed of 16 tubular members as shown in Figure 7.71.

The final structure was designed for four bases, each being the starting point and foundation of four robots and resulting in an overall robotically fabricated structure. In the generative design set up, each base started with a single robot moving upwards and being attracted by the other three, which started from the other bases, thus assuring coherence of the structure and bundling at the top. This was done in sequence such that one robot was the lead for the whole structure, and all other robots could follow this lead in accordance with the other parameters. A height threshold could be set for when we wanted the individual structures to cross, giving us the design ability to create an open space within the structure. This was also constrained by the maximum tilt angle of the robots and the spacing of the bases. This meant that having the four bases closer together made a crossing of individual tubes possible at a lower height, while positioning the bases at a greater distance meant a higher first meeting point could be expected. After this initializing step, all of the other robots started sequentially with separation, alignment and cohesion as the guiding principles, adhering to the previously discussed parameters and constraints of this robotic system.

The final a structure was 3D scanned (Pix4D software) and compared to the original CAD file, with varying results for accuracy. While some columns stayed within a reasonable offset location (20 cm – 40 cm) from the origin in the CAD file other columns had a more dramatic offset location of 40 cm – 60 cm as seen in Figure 7.70. On very few columns the IMU or mechanical drive seemed to have failed thus the robot was wandering off track completely. However, these results present good overall results for pure IMU trajectory control and more accuracy should be achievable through additional on-board sensing discussed later in this chapter.

7.8 Ideas on Post Strengthening of Structure

In a large-scale structure in may be beneficial if not necessary to use additional processes to strengthen some critical elements or loadbearing columns in post. Basic experiments have been done, filling segments of robotically fabricated tubes with structural materials.

7.8.1 Concrete

Concrete is an obvious contender as a filler material.

Bader, Mediated Matter.

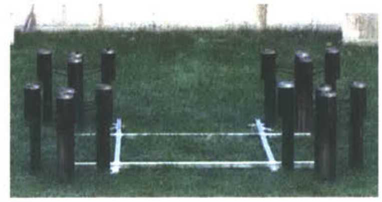

Figure 7.66: Jig positioning bases for robot initial configurations.

Figure 7.67: Calibration of robots in the foundation bases.

Figure 7.68: Robots starting to build structures sequentially.

Figure 7.69: Nighttime construction.

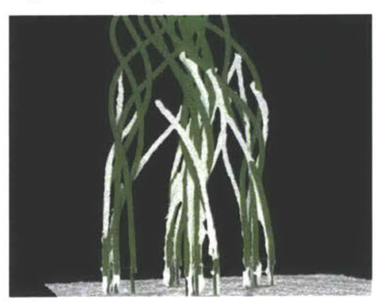

Figure 7.70: Final built structure 3D scanned and compared to original

CAD file.

7.8.2 Fiber Reinforced Concrete

Even more strength can be expected from fiber-reinforced concrete as a filling material. While the outside fiber-wound tube encases the material, constraining its expansion, the fiber reinforcements inside the concrete should provide more strength under tensile stress.

7.8.3 Mycelium

A more sustainable filling mixture that could work as a filling material strengthening some of the tubes in large-scale structure is a product based on *mycelium*. A mixture of the base components of shredded wood and *mycelium* spores is hydrated and left to grow. The *mycelium* is a fast-growing fungus whose roots connect and combine the whole mixture into a solid and lightweight structure (Ecovative 2017).

Figure 7.71: Side angle view of final hour of construction.

7.9 Material Analysis

7.9.1 Compression tests

7.9.1.1 Compression testing Experimental Design

Six-inch linear sections of straight tube were segmented from longer samples and tested under compression on an Instron machine to determine their compressive yield strength. Comparisons between the samples were made to evaluate consistency between samples. Inconsistencies are expected due to imperfections in the tube fabrication (resin distribution, layer overlap, and the resins rate of curing).

Figure 7.72: Finished structure in sunlight, showing translucency through the glass fiber tubes

7.9.1.2 Initial Compression Test Results

Four initial compression tests were performed on sample sections of the glass fiber composite tubes made by the Fiberbot, which show large inconsistencies in their compressive strength. Initial tests showed long regions of low loading where the top of the tube was only in partial contact with the platens of the Instron[41] . As the smple was initially loaded, a thin asymmetric gap was visible on one side of the tube. As the tube was loaded and the Instron gauge length decreased so did this gap, and it fully closed as the load cell approached 5kN. As the top and bottom cuts on the tube section were not completely parallel the load from the Instron was distributed unevenly throughout the sample. Sample 2A was intended to address this inconsistency with re-designed fixturing of the sample. In Figure 7.74 is a chart with the raw data collected from these compression tests. Sample 2A, which supported roughly 5 times as much as sample 1B and 1C, was fixed in a circular pocket. The pocket was filled with epoxy to secure the sample. After the epoxy cured fully the top and bottom metal plates were milled flat to guarantee even loading (Figure 7.73). In contrast sample 1A, 1B and 1C were simple cut sections. Though their top and bottom surfaces

[41] Instron 5985, Center for Bits and Atoms at MIT.

were roughly parallel, placing a bubble level on them showed slight inconsistencies.

It was observed that samples 1B and 1C failed due symmetric buckling around a layer overlap, where as 1A and 2A developed asymmetric cracks which propagated radially around the circumference of the tube. Delamination between the fibers is clearly visible and can be seen spreading as the tube fails.

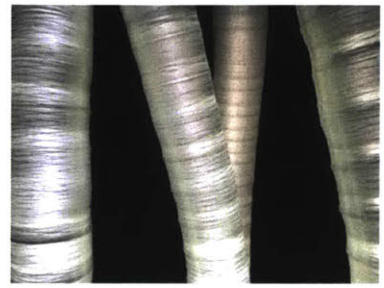

Figure 7.73: Tubular structures lit from inside.

7.9.1.3 Compression Test Conclusions

Further testing of material properties of the robotically fabricated columns is needed to fully evaluate and compare it to other known material systems. These basic tests show that there is still work to be done in order to create a more consistent winding especially, between segments. Also, further exploration into the maximum wind angle, and varying the patterns within segments sequentially may significantly improve overall strength. However, from early tests it can be said that the structures produced in this first demonstration of the robotic system, are strong enough to self-support themselves during fabrication and as a finished structure under wind speeds of 38 km/h (and maybe more).

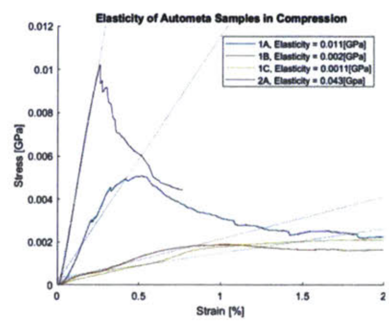

Figure 7.74: Plot of Instron compression test using Fiberbot tube samples. Experiments done by Sara Falcone, Mediated Matter.

7.10 The Fiber Bot in Comparison to Existing Distributed Robotic Large-scale Structures

So some may ask when can we use it and how does it compare to other building technologies in research. Generally, it is difficult to compare current distributed fabrication approaches as each system has a different agenda and problems to tackle. However, I will try to draw some comparisons between the Fiberbot system and two robotic projects, which achieved large-scale construction, in order to place the Fiberbot and its way of construction into the wider landscape of distributed fabrication approaches for the architectural scale. As discussed previously, ETH's *Flight Assembled Architecture* presents the only truly large-scale example of multiple robots—in this case quadrocopters—working together in construction. To achieve this, a completely controlled environment was needed with high-end tracking cameras (Vicon T40 System) positioned all around the indoor space (Augugliaro et al. 2014). In contrast, the aim of the Fiberbot project is to be able to construct outdoors without the need for any external sensing or tracking needs. For now, both systems use a centralized computational system, providing precise path trajectories to the drones or robots to avoid collision. Even though drones definitely have the potential to overcome these limitations in the future with better onboard sensing capabilities, this current approach does not fully address the gantry problem as it still requires a large pre-structure to hold the tracking system and shield it from the unpredictable outdoor environment. Additionally, the material systems are also very contrasting. While the drones assemble lightweight non-structural bricks as of their limitations in carrying significant loads the Fiberbot uses a lightweight but highly structural material system—fiber-composites—of potentially varying density gradients and functionality. When it comes to the shapes that are possible both systems have their merits and limitations—for example, rectangular bricks have limitations in creating

Figure 7.75: Glass fiber composite tube in aluminum fixture prepared for Instron testing by Sara Falcone, Mediated Matter.

overhangs, but can be stacked tightly to create closed features, whereas the Fiberbot system relies on a 'loosely' woven architectural wall while being able to tune the material performance on the fly—one residing in the world of rectilinear shapes and the other in a curved one. I believe that when we tackle novel approaches in architecture, such as swarm construction, we should not try to recreate the existing ways of building e.g. stacking bricks, but also aim for a new kind of architecture that reflects the methods that gave birth to it and *hopefully* be surprised by the outcomes previously unthinkable. Whether curvy woven fiber wound tubes will replace the brick in architecture anytime soon is not the point. It is the pursuit of novel technology through which new form and functionality can be achieved, even if some other older forms (e.g. rectangularity) and some functionality (e.g. sealed volumes) are left behind—at least for now. The very idea of the Fiberbot is that the internal construction provides a way of free-form construction that cannot be achieved by assembly robots. The *Mini Builder* project is the second example that has achieved large-scale construction using robotics and a heat curable polymer compound. Here, the limitations in shape are continuous surfaces and the tethered material approach, using a large back-end material supply system which needs to move with the robot at all times, thus making it a small robot attached to a large manually driven one on the side (Jokić et al. 2013). The Fiber Bot can also be described as tethered, but instead of being attached to another system it is constrained by the very structure it builds, and the material system does not come from the outside of the structure but through it, thus enabling free-motion (within previously established constraints). When comparing the Mini Builders and the Fiberbots material systems, the Mini Builders approach of using a two-part heat curable epoxy compound stands in contrast to the fiber composite approach of the Fiberbot. Although both material systems are continuous (not prefabricated blocks or beams) the polymer compound used by the Mini Builders creates a solid homogeneous layer-by-layer material structure without room for density variation or functional tunability. In contrast, the Fiberbot's goal is to vary and grade the material properties of the material during fabrication e.g. having thicker and more compact winding at the base gradually decreasing density towards higher parts. If fiber composites are a desirable material to build with, which I think they are for reasons discussed previously—among them the ability to precisely vary material distribution—the internal robot approach is a necessity. Applying fiber and resin requires a substrate and most commonly fabricated fiber composite structures use a mold or scaffolding structure to apply the fiber composite. The Fiberbot uses the inflatable membrane as a mold and feeds the fiber centrally through the robot in order to apply a continuous material. When winding straight fiber composite tubes in conventional manufacturing, the mandrel is turned (spins) and the fiber and resin are applied externally, while this is practical for straight tube manufacturing it is not for curved and site-specific applications in a distributed system as the tubular member that is being made has to spin. This leaves the other option of spinning the winding applicator instead and thus the fiber. But when spinning a continuous material such as the fiber, either the material is on board the winding arm and thus limiting the quantity of material (length of fabrication before replenishment) or it is fed centrally to the winding motion in order to prevent entanglement of the fiber. These constraints dictated by the use of a versatile material system—fiber composite winding—have led to the current internal robot design. By no means will the Fiberbot provide answers to all the issues related to large-scale swarm construction but rather demonstrates the first structural large-scale structure. By this approach, the aim is to eliminate the gantry or large controlled indoor space as well as an extensive tethered backend system.

7.11 Future Development of the Robotic System

7.11.1 Future Research in Current Robotic System

Direct improvements of the robotic system presented here mainly concern the backend feed system as well as the fatigue life of the linearly moving parts, namely the FFC cable and the 'snake' assembly, moving resin from the robot body to the rotary drive assembly.

As previously mentioned, the transport of a viscous and sticky material such as the resin used here over long distances through a small diameter tube presents challenges, which are not fully addressed in this system. Several pump failures meant repeated repair during fabrication, which slowed down the process significantly. The reason for these failures is simply the high-pressure build up, which creates high friction between the silicone tube and the wheel and inside wall of the peristaltic pump, resulting in silicone tube failure. This may be addressed by moving to a pneumatic pump system as a backend feed system and a pinch valve for tight output control on the robot. There are probably challenges associated with this approach as well, as the pressure drop throughout the 10-meter tube up to the robot's limits start and stop control and possibly creates a delay in response, but these may be overcome by additional onboard control features such as valves or micro pumps.

Fatigue and creep of the FFC and the linearly expanding silicone tube 'snake' design is partially due to very tight space constraints in this robotic system. The FFC is repeatedly bent over an edge inside the robot with a slightly too s-all bending radius. This results in a kink at the point of this specific edge and eventually breaks the copper contacts. Basic improvements that reduced this sharp edge to a smoother and larger radius already dramatically increased the life of the FFC. However, in order to create a truly robust system more space is required to house this FFC in order to prolong its life to its maximum specifications.

The design of the expandable silicone resin tube fails at the silicone rubber bands attached to hold it in the 'snake' configuration. Here, braiding several small diameter silicone tubes to create the expandable design led to an increased life expectancy. As the braiding increases the length of the individual elastic tubes while keeping overall the same length, less strain is put on the individual elastic tubes as repeated expansion occurs. Further improvements may involve a single custom molded piece as failure still occurs at random intervals, but consistent location, at the connecting glue joints.

Further improvements are concerned with the accuracy of the IMU reading in correlation with the base drive assembly as overall drift still seems to be significant. Potentially additional sensing capabilities are required for better path accuracy as some of the tubes ended up approximately half a meter off from where they should have been at 4.5-meter height. These may include visual sensing by an on-board camera tracking specific spots on the ground but may also be resolved by inter-robotic communication and obstacle (other columns /robots) detection as will be described in the next section as robots keep their distances at least relative to each other.

Figure 7.76: Varying the diameter of the fabricated tube by winding and inflation sequence.

We sometimes joked that we have created an artificial intelligence as the robot would do something very unexpected and we couldn't find the root of the problem/intelligence. So generally speaking this robotic system worked quite well overall but sometimes, and only sometimes, it would miss an instruction or the IMU would wander off. So, there is still some debugging to do in order to create a robust system.

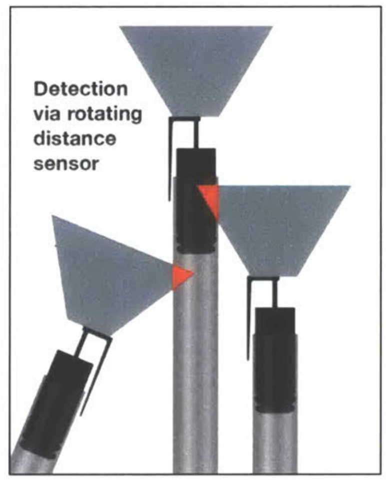

Figure 7.77: 3D robot column detection via short range (20-50cm) rotating distance sensor

7.11.1.1 Another Future Level of Hierarchy in, of and for Tunability

Another layer of variation could be added by inflating and winding sequentially. To start winding, the mandrel needs to be inflated sufficiently in order to de-mold from the resulting tube as well as leaving enough space for the base drive assembly to move through the tube. However, a varying tube diameter should be achievable by tightly controlling the inflation and winding sequence. It may be noted that feedback on the inflation volume may be required as the pressure changes and the pumps air output may vary.

7.11.2 Algorithms across Scales

The explorations at the core of this thesis, including the preliminary experiments and the main project, embody a new approach to fabrication-based algorithmic design inspired by swarms. Throughout this thesis, methods for creating processes for path navigation on the level of a single bot from a digital fabrication perspective, deliberations regarding collision control between bots, and reflections on the 'swarm' as a whole insofar as it may respond and adapt to its environment; have been woven together to form a novel design approach towards the integration of swarm-based systems in architectural design. At times, in place of dynamic computational algorithms and template method patterns, I have explored decision-making processes informed by the FiberBot units themselves; I consider these explorations to be of the category of *fabrication-based algorithmic design* and am confident that we be seeing more of this line of work in the future.

7.11.3 Future Directions

In order to bring the Fiberbot project back into the larger vision and realm of energy, matter and compiler future developments may include the use of photovoltaics 'feeding' the robots with solar energy. Also, the material system could become one that uses natural fibers and resins such as cellulose and chitosan with photoactive monomers added to create a more sustainable materiality. Further, I see very interesting benefits to woven architectural structures; what if a building could bend and flex under the dynamic loads of heavy snow, windstorms or the forces of an earthquake? For now, the Fiberbot uses glass fiber and epoxy resin (not the most sustainable materials). However, in the future some tubular members may be made from hemp and biodegradable resins, soft and hard binder materials, fluidic fibers, biocompatible materials for plants or bacteria to grow on, eventually replacing and potentially advancing the robotically made structure naturally. I believe that the use of fiber composites holds great promise for future investigations and thus this system shall not only serve my PhD but hopefully become a platform for further material explorations as research in fiber technology as well as biocompatible and biodegradable materials advances. Eventually, the robotically fabricated structure may become the scaffolding for yet another biological system to grow on, bringing back the idea of technological/biological and templating/augmentation. Ultimately the aim for this fabrication approach and system is to achieve the construction of large-scale structures implementing multiple bots designed to digitally construct in a materially tunable and collaborative manner. Each robot could be equipped with a unique fiber, or combination thereof, such that a hierarchical system of material gradient variation can be established. As previously discussed the proposed hierarchy consists of the following elements: varying material *distribution* across a single strand via winding patterns (*e.g.* within a single tubular construct), and varying material *properties* through the amalgamation of various fiber types and their specific trajectory (*e.g.* the 'path' or trajectory of fabrication).

Environmental sensing may provide the logic for the designed structure while it is constructing, taking into account immediate spatial constraints present in the immediate environment as well as orienting its structure in accordance to the cardinal points for example maximizing sunlight exposure or shielding.

The sensing capabilities need further research. The current system deals with orientation and driving only by encoder and IMU reading while environmental sensing of the surroundings, obstacle avoidance and communication are non-present. A next step in this project would be to include a directional light sensor capable of tracking the movement of the sun as a global directional coordinate. Additionally, a distance sensor should be incorporated for detection of other tubular structures and robots, being capable of sensing not only the distance but also orientation of tubular members. By placing it on the rotating arm, which can be tightly controlled through the stepper motor, it could create a sensing 'funnel' that also can detect orientation of a given tube nearby by measuring the closest point and two far points in accordance with expected diameter of tubes. This information may be enough to create a rule-based system, which is based on all the known factors of tube diameter, base starting configuration and sunlight path and current state and can compute from this information an 'optimal' path for its next section without a centralized approach.

Some of the established computational approaches developed in simulation for the robot and the design of the structure in the Mediated Matter group may help on the way in achieving a rule-based logic for the robots which is not reliant on a centralized computer giving instruction but rather through on-board decision making.

Ultimately, I imagine a future where the design of a building is largely influenced by the environment it is placed in. The designer is mainly concerned with function over forms and where the aesthetic value of a building is derived from the designer's careful planning of functions. Much like a tree planted in the built environment adapts to its surroundings while it grows, to maximize the nutrients required to grow it from its roots in the earth to its crown for maximum sunlight exposure and carbon from the air. In this future, swarms of robots of varying functions could act not only in accordance to predefined code in their construction but sense what is required and act on it. Some robots may collect material and energy, others may build the structural columns, while others fly around connecting these columns with tensile structures, and others again make sure material supplies are sufficiently replenished, ideally in every sense from the immediate local environment.

Figure 7.78: 3D-printed robot parts.

Figure 7.79: DC encoder gear motors wiring before assembly.

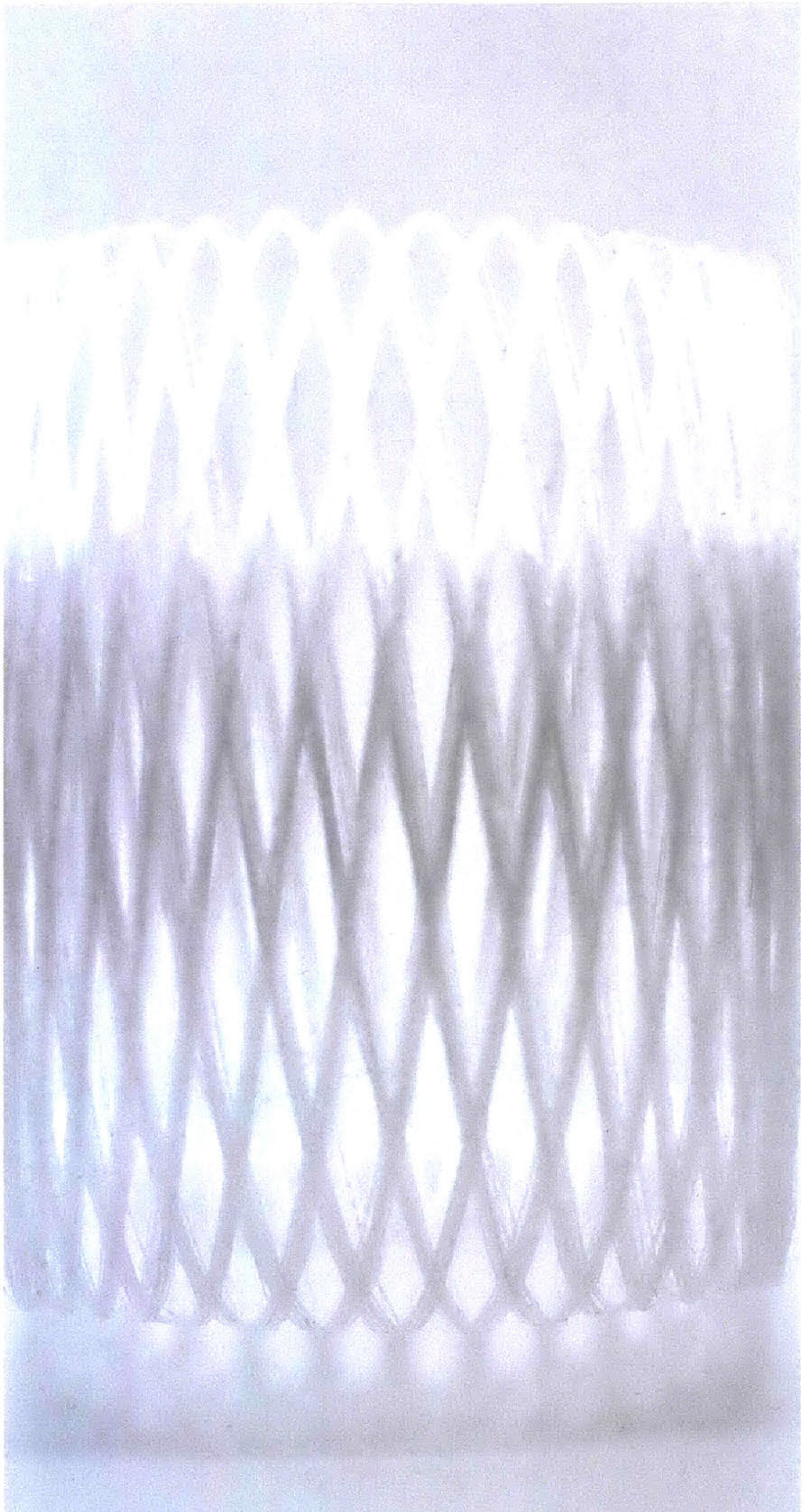

Figure 7.80: Wind pattern sample, made with the stationary winding rig. Image by Nassia Inglessis, Mediated Matter.

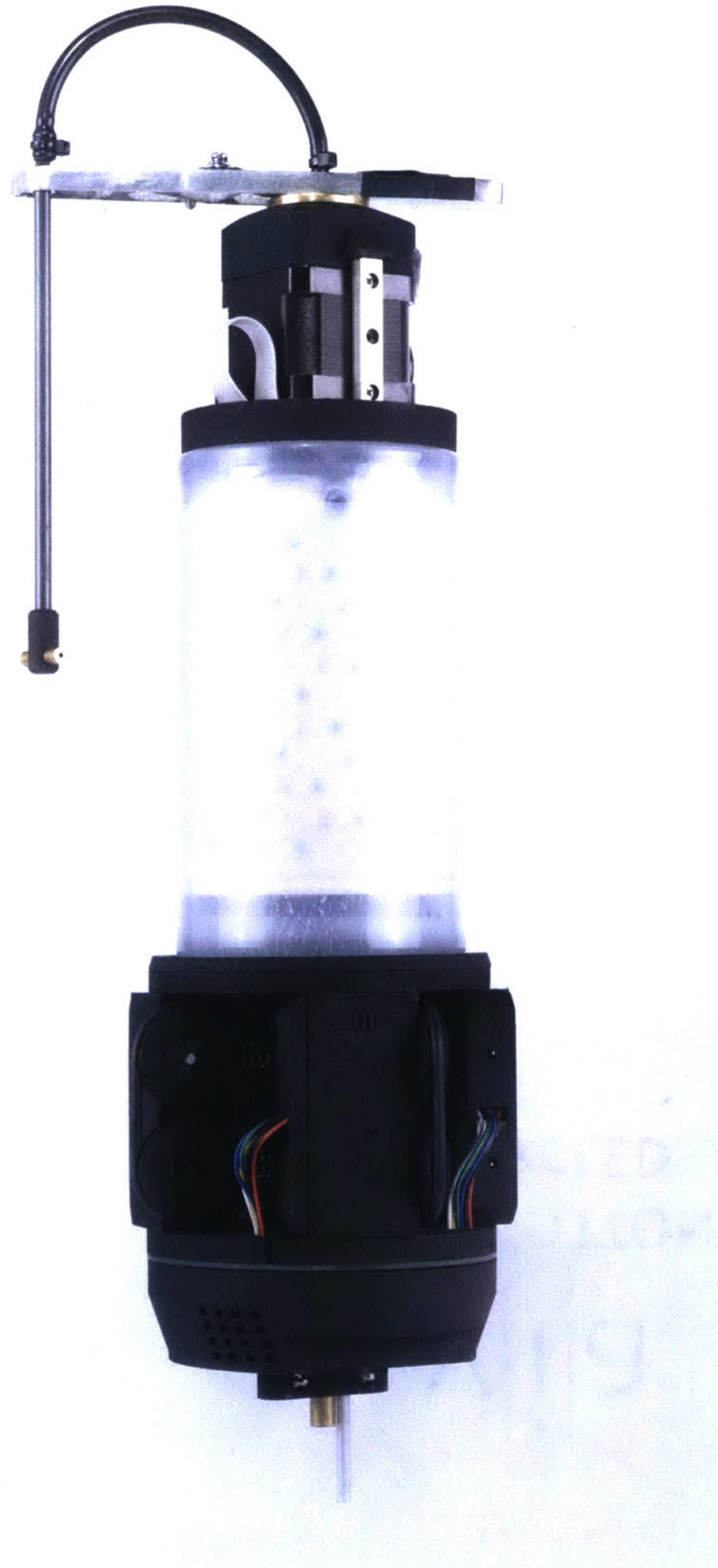

Figure 7.81: Fully assembled Fiberbot robot.

Figure 7.82: Fiberbot backend system, pump and resin bottle wrapped in wiring and tubing.

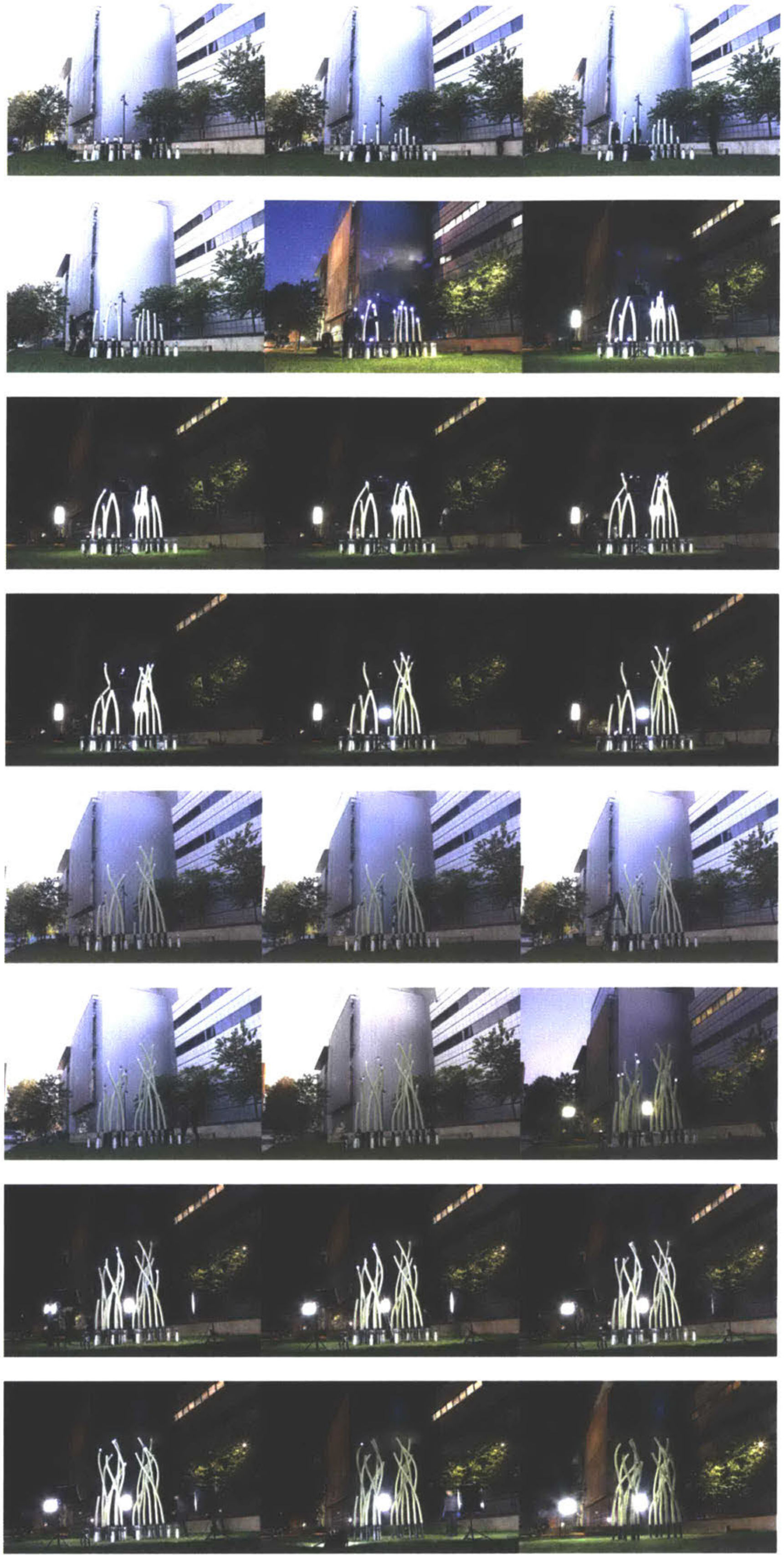

Figure 7.83: Image sequence of Fiberbot demonstration structure built over the course of two days.

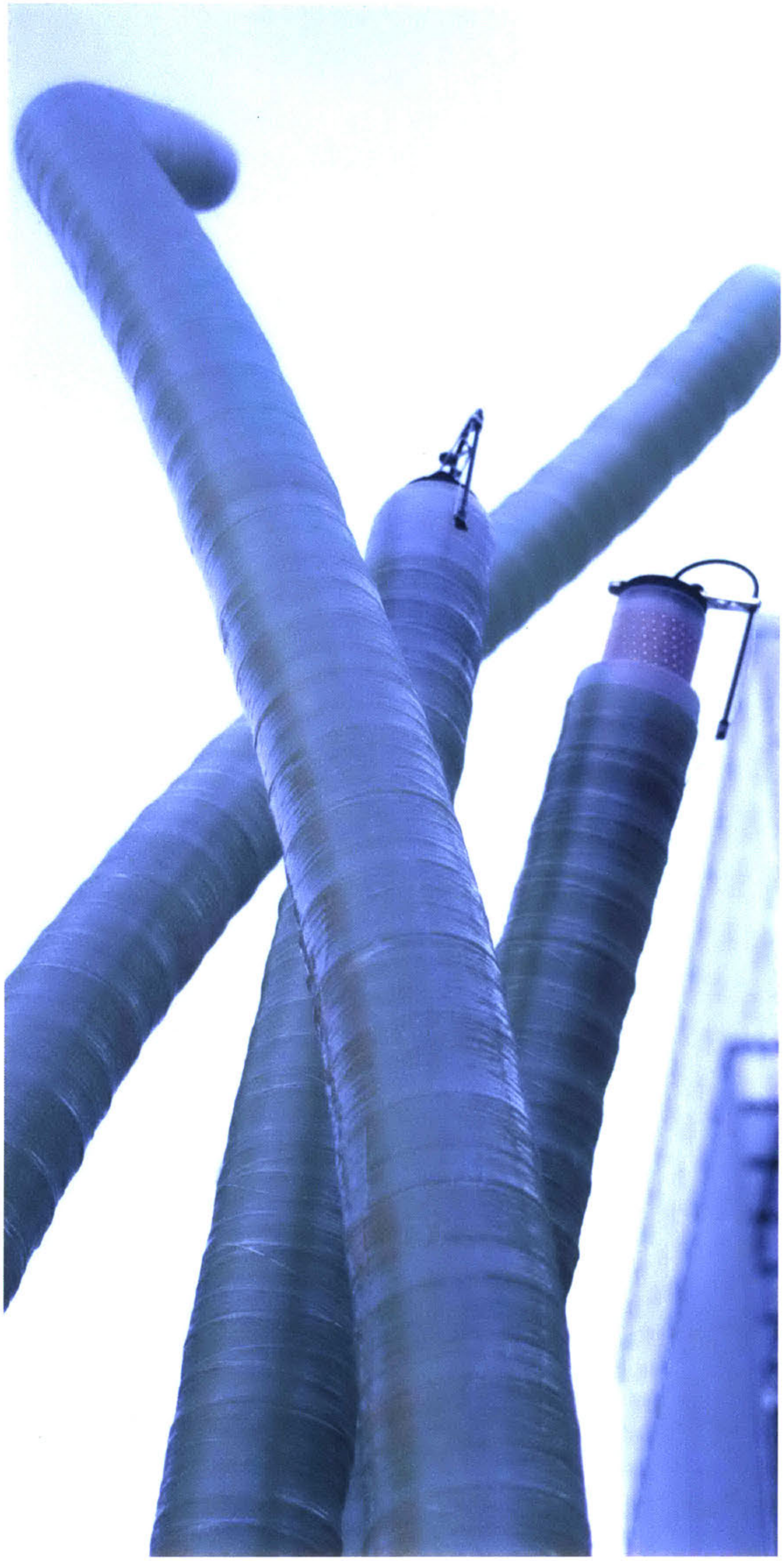

Figure 7.84: Columns being erected by the Fiberbots.

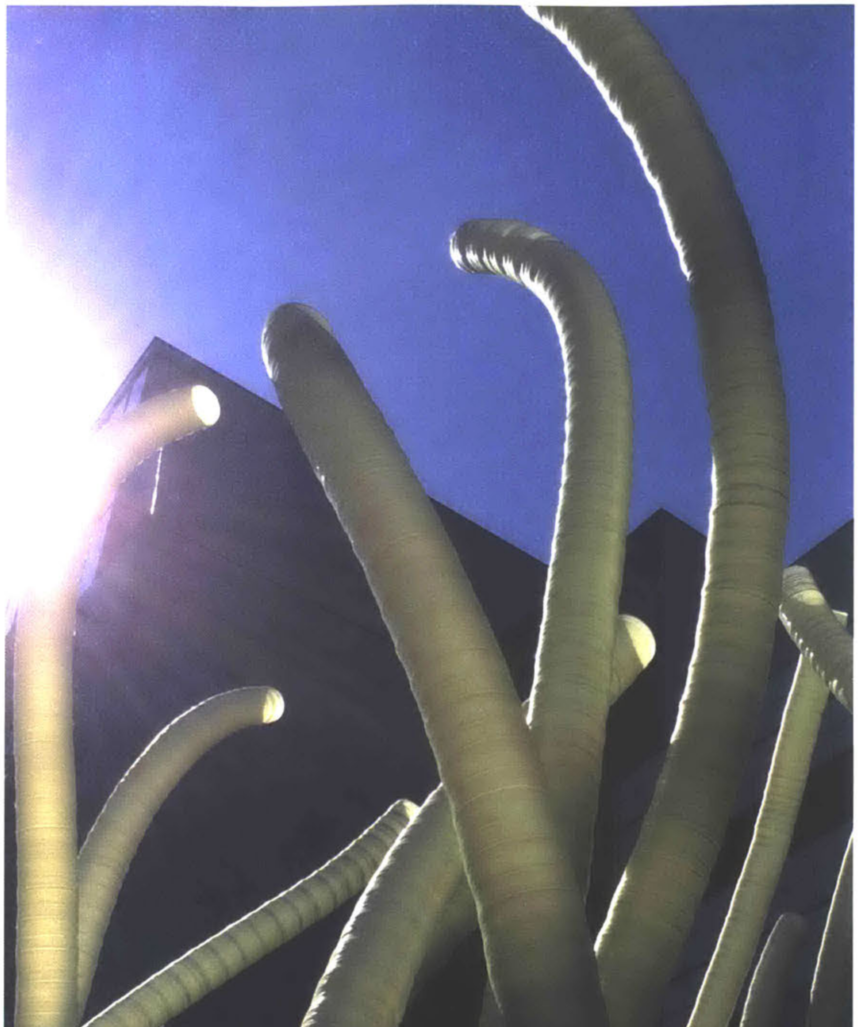

Figure 7.85: Robotically fabricated tubular structures post-curing in sunlight.

Chapter 8

Discussion
Towards Swarm-based Design

8.1 Towards Swarm-based Design and Fabrication

Distributed fabrication could usher in a new era of architecture that could in turn enable new structural forms and new functionalities across scales. In design and fabrication, the limits on what is achievable often come from limitations in fabrication hardware and the sophistication of the materials these machines can process. While we look to Nature for answers about how materials are processed and 'assembled' or grown, we too often try to emulate selected, isolated parts of it in digitally fabricated constructs that resemble the geometries but fail to capture the true genius of their multilayered, graded, and efficiently produced counterparts in Nature. The question, then, is how the very fabrication technology can emulate nature's *ways* instead of just her *product*. As shown in some of my case study projects, one answer may be to integrate Nature herself directly into the fabrication process and thereby access some of her still-hidden secrets by directing, orchestrating and templating agents, e.g. silkworms, to make for us what a digital machine cannot.

In the case of the Silk Pavilion project, the material—silk—is not conventionally harnessed by manual labor, or brought to us in forms and shapes we desire by long and unsustainable processing chains. Rather, the silkworm is embraced as both a fabricator that provides the sophisticated material and as a collaborator in design. This is one of the core elements of this thesis, as Nature not only provides material but also designs forms and even guides some aspects of this building process via templating or augmenting material constructs in ways that digital fabrication technologies are not yet ready for.

The light-guided ant apparatus provides another case study for directly tapping into Nature's genius. In this case, the individual ant is a fabricator, but since ants are eusocial insects that communicate with each other, multiple ants provide a distributed fabrication system—unlike silkworms, they already work collaboratively and thus can be templated and guided as a collective entity. This provides an interesting shift, as individuals pass on information within the distributed biological fabrication system and thus provide the possibility for a global template by means of local stimuli. However, ants lack the highly sophisticated material fabrication of the silkworm and 'only' excavate material.

The initiating steps taken in the Silk Flock experiments provide yet another shift in design, demonstrating how a sophisticated material provider and its deposition genius can be harnessed and globally steered to densify and prioritize certain areas over others on a given template. Projecting this approach onto the background of a given feedback control loop can be expected to achieve a much tighter correlation between desired outcome and actual deposition.

While the Synthetic Apiary stands out as an environment without direct fabrication advances (meaning the bees do what they do), it still represents a meaningful direction for swarm-based design. Trying to facilitate synthetic environments inhabited by living organisms is a first step in understanding more about what is required for such a complex organism as the European honeybee to survive and even thrive in an artificial set-up. When thinking about why this might be useful apart from fabrication experiments, two things come to mind instantly—space exploration and farming. On Earth, insects are dying at a rapid rate, with a recent study concluding that 75% of the insect population in Europe has been lost in the last three decades alone (Hallmann et al. 2017). The Synthetic Apiary explores questions of how the manmade environment can also serve as a space for cohabitation with other biological organisms in architecture. An application in space may seem more far-fetched but when we think about the habitation of, for example, Mars, we will also need to think about farming in other planets and how to create eco-systems that support the production of food there. Bees as pollinators may be required (or at least desirable helpers on that mission) and thus the study into how to assure their survival in artificial environments.(Gibbens 2017) Projections presented in this thesis on how to include bees in the fabrication paradigm, included robotically templated and gravity-controlled fabrication strategies, serve as future direction and can only be verified in further research.

However, when it comes to scaling up distributed fabrication processes observed in Nature into the architectural realm, we may still have to rely on the development of digital counterparts in distributed robotics, as the scale of the human built environment surpasses that of the insect inspiration. While the fully automated digital fabrication of architectural scale constructs has yet to be developed, and the final project of my PhD may only provide a step towards this goal through the design and deployment of a multi-robot swarm that constructs a self-supporting structure, automation that mimics some of Nature's fortes may be a good-enough stepping stone towards the more holistic goal of a 'techno-biological and hierarchically organized swarm of design fabricators' on the large scale.

The Fiberbot project takes a design fabrication approach by developing the fabrication hardware first, in order to demonstrate the fully automated construction of a large-scale structure, which is algorithmically designed using swarm-inspired computational design strategies. Although the individual robots still 'talk' to a central computer rather than communicating among themselves, the system demonstrates that such distributed fabrication systems may be useful in tackling the automation of architectural construction. Probably the most significant advance of the Fiberbot project lies in the automation of large-scale constructs by means of robotic fabrication, as small individual machines/robots are able to scale fully automated construction or, at the least, structural columns. Further, it was shown that the fabricated columns could be graded materially, in varying wind pattern formations during fabrication. For the present work, most of these gradient material experiments were done in an experimental stationary test set-up and not on the final structure itself. However, on the large-scale structure each column also had a gradient throughout, with decreasing material deposition towards the higher portions of the columns. This approach shows that this process can indeed grade material for a more efficient use of resources, as less material is applied in accordance with the decreased load each individual column has to bear.

Swarm-based design is demonstrated in several digital and biological fabrication case study projects and may serve other designers as a starting point for their research endeavors. Some questions of scale and the principles of templating and augmentation have been answered, while others still require further investigation.

8.1.1 Contributions

This research presents contributions to knowledge in several domains. 1) In the domain of design by proposing new approaches through a framework applicable across disciplines, including biological and technological synergies, 2) in the domain of robotics by designing and building a novel, distributed fabrication hardware system and demonstrating the automated construction of a 4.5-meter tall structure built from fiber composites, and 3) in the domain of digital fabrication by presenting novel, materially tunable digital fabrication technologies.

- Enabling automated digital construction and manufacturing using 'raw' materials rather than pre-shaped components (continuous vs. brick). This was demonstrated through the development and deployment of a multi-robot fabrication system.

- I demonstrated two classes of swarm-based design—building swarms and guiding swarms—interfacing with their biological counterparts to respond to external environmental stimuli. The Silk Pavilion, Light-guided Ants and early developments of the Silk Flock present valuable insight into co-fabrication between technological and biological systems.

- The biological case-studies and experiments developed and presented in this thesis create a theoretical foundation and experimental platforms for swarm-based design that is: 1) guided by strong 'social' communication; (2) able to generate materials with variable properties; and (3) sustainable (i.e. does not rely on external energy resources but can potentially use natural resources).

8.1.1.1 List of Papers and Patents

Additive Manufacturing of Optically Transparent Glass
2015 Klein, J., Stern, M., Kayser, M., Inamura, C., Franchin G., Dave, S., Weaver, J., Houk, P., Colombo, P. and Oxman, N., Journal of 3D Printing and Additive Manufacturing, Volume 2, Number 3, Pp. 92-105

Designing the Ocean Pavilion: Biomaterial Templating of Structural, Manufacturing, and Environmental Performance
2015 Mogas-Soldevila, L., Duro Royo, J., Kayser, M., Lizardo, D., Patrick, W., Sharma, S., Keating, S., Klein, J., Inamura, C., and Oxman, N., Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, Amsterdam

Modeling Behavior for Distributed Additive Manufacturing
2015 Duro-Royo, J., Mogas Soldevila, L., Kayser, M., and Oxman, N. , Proceedings of the DMSC Design Modeling Symposium, Copenhagen , Accepted for publication

Silk Pavilion: A Case Study in Fiber-based Digital Fabrication
2014 Oxman, N., Laucks, J., Kayser, M., Duro-Royo, J., Gonzales-Uribe, C., FABRICATE Conference Proceedings, Fabio Gramazio, Matthias Kohler, Silke Lan enber (eds.) ta Verla, Pp. 248-255

Biological Computation for Digital Design & Fabrication
2013 Oxman, N., Laucks, J., Kayser, M., Gonzalez Uribe, C., and Duro-Royo, J. , eCAADe: Computation and Performance, September 18-20, Delft University of Technology (TU Delft), Delft, the Netherlands

Robotically Controlled Fiber-based Manufacturing
2013 Oxman, N., Kayser, M., Laucks, J., and Firstenberg, M., Green Design, Materials and Manufacturing Processes published by Taylor & Francis , ISBN: 978-1-138-00046-9

Freeform 3D Printing: toward a Sustainable Approach to Additive Manufacturing
2013 Oxman, N., Laucks, J., Kayser, M., Tsai, E., and Firstenberg, M., Green Design, Materials and Manufacturing Processes published by Taylor & Francis , ISBN: 978-1-138-00046-9

Methods and apparatus for AM of glass, U.S. Patent Application 14697564, filed April 27, 2015.
Klein J, Franchin G, Stern M, Kayser M, Inamura C, Dave S, Oxman N, Houk P,

In the following section I will discuss potential future work and a wider view on swarm-based design and distributed and materially tunable digital fabrication.

8.2 Future Directions

Single-node machine processes can be used to template distributed biological systems and thus can be classified as another node in a larger fabrication and design cycle.

When thinking of swarm/distributed systems, I mostly refer to identical robots or organisms working collaboratively to achieve a higher goal together. However, there are also hierarchies embedded in most biological examples of swarm fabrication systems, where either individuals have differing tasks depending on age, as in bees—even if fabrication agents like bees fulfill the description of self-similarity, they have varying occupations dependent on age and thus have a hierarchical yet distributed order within the system. Additionally, most eusocial systems have a single queen, which is the mother of all agents.

In future work on swarm-based design, some of these concepts may be transferable to larger fabrication systems where computation, CNC fabrication and biological templating are united to fulfill a common goal. In fully technological systems, collaborative, hierarchically organized robotic fabrication tools may exist, where the robots' function may vary in such a way that they complete varying tasks but work towards the same global goal.

In most material systems as well as most processes in Nature there is some kind of hierarchical order, with multiple contributors to single-material systems. When considering shells, silk, or trees you will always find a multilayered approach to fabrication with gradients of multi-material distribution (Gibson 2012). As previously noted in the discussion about the tunability of materials, the combination of fiber and matrix—fibroin and sericin in silk, chitin and calcium/calcite in hard shells, cellulose and lignin in trees—gives most of these materials the unique properties we strive to replicate. But it is the seamless integration of processes that leads to these superior natural material systems, which result from a holistic fabrication approach that avoids the assembly of parts in post. What if we could replicate some of these ideas, even in a sequenced manner where each process builds on top of another to approach a more holistic design and fabrication protocol?

8.2.1 Impact and Future of the Research in the Mediated Matter Group

Many of the processes described here are still in development. As any researcher and designer knows, there is no end, no finish line in sight, but rather continuous exploration. I hope that some of my endeavors will inspire other researchers to build upon it and continue thriving and developing new and better, or sometimes just *other* processes, to MAKE and DESIGN the built environment in ways we haven't yet discovered.

Some of the processes I developed are already finding new forms and explorations for future work. From my work before MIT, solar sintering has become a verb and is being further explored by ESA and others for building futures in space (Meurisse et al. 2016, Labeaga-Martínez et al. 2017, Mueller et al. 2016). The Silk Pavilion and related processes such as CNC fiber deposition has been further developed in the group and is starting to enter the three-dimensional realm. Additionally, the basic experiments in thermal templating are being explored in more depth while building on the previous work—the silkworms are back!

Glass 3D printing has also come a long way since the first prototype printer, and is continually being further developed and constantly extending its capabilities.

Finally, as discussed in a previous section, the Fiberbots already have integrated wiring for potential sensing capabilities and further software and backend development. I also hope to see work being built directly on this platform.

I'm honored, grateful and proud to have been part of so many interesting and forward-thinking projects that spark interest and trigger ambition in others to pursue these paths, which begin so humbly and in the best cases grow up to inspire.

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