Robotically Controlled Fiber-based Manufacturing as Case Study for Biomimetic Digital Fabrication

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

1 INTRODUCTION

1.1 Background

Additive manufacturing and digital fabrication processes such as 3D-Printing typically involve the layered deposition of materials with constant and homogeneous physical properties (Gibson *et al*.). Yet all natural materials and biological systems are made of fibrous structures that are locally aligned and spatially organized to optimize structural and environmental performance (Mitchell and Oxman 2010). Furthermore, construction processes found in the animal kingdom such as woven spider nets or aggregate bird's nests are characterized by the animal's ability to 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 (Benyus 2002; Robbins 2002; Hansell 2005). Many of these constructions are "designed" by insects well known for their ability to construct highly sustainable structures made of fiber composite materials such as silk (Sutherland and Young *et al*. 2010).

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

1.2 Problem Definition

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

2 FIBER-BASED CONSTRUCTION IN NATURE

2.1 Introducing the Silkworm Bombyx Mori

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

2.2 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 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.
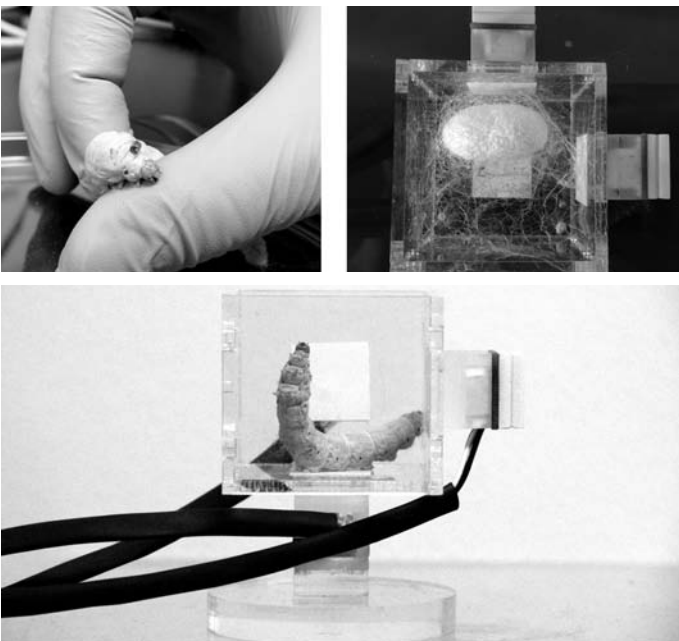

Figure 1. Motion tracking of the silkworm *Bombyx mori* using magnetometer sensors and a 1mm x 2 mm magnet.

An experimental sensor rig 40 mm X 40 mm X 40 mm in dimension was developed using magnetometer sensors placed on 3 planes of the cube. This allowed for data capturing from a 1mm X 2 mm magnet attached to the silkworms' head (Figure 1). After attaching the magnet to the silkworms' head, 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 2.
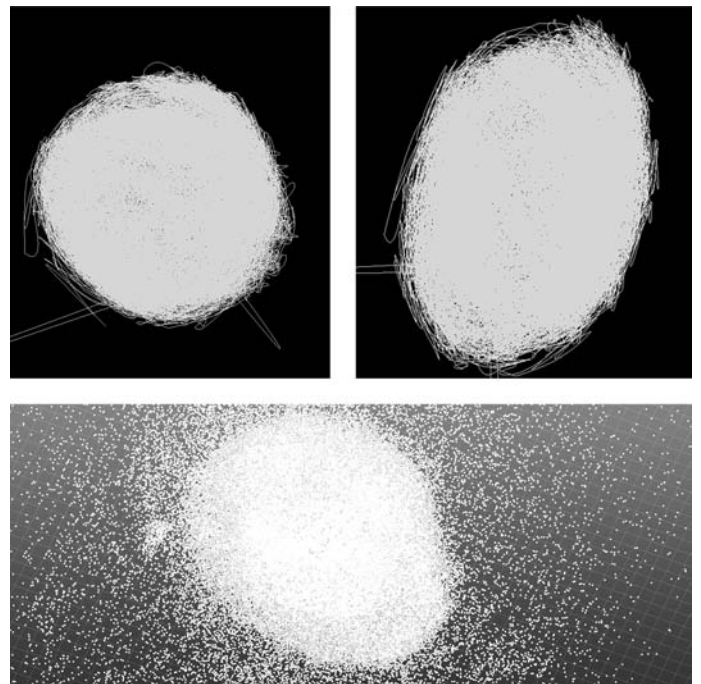

Figure 2. Motion path (top) and point cloud (bottom) in Generative Components (GC) software.

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

2.4 SEM Imaging across Multiple Scales

In order to investigate local fiber placement of the cocoon as well as to gain a better understanding of

the scaffolding structure, SEM images were taken of the outer layer of the cocoon.
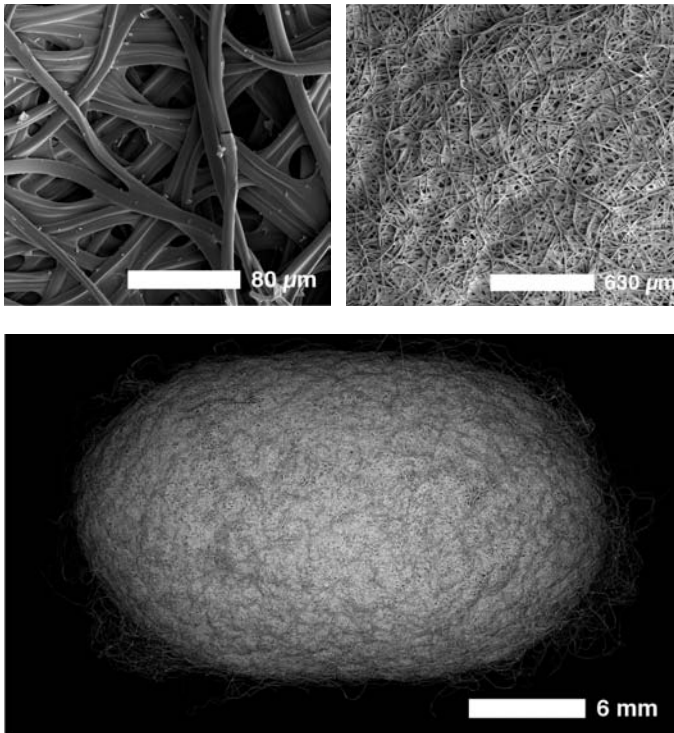

Figure 3. SEM images of the silkworm *Bombyx mori* cocoon across multiple scales (Photo credit: James Weaver, 2013).

Figure 3 shows the overall all cocoon form. Its shape and curvature radii largely depend on the silkworm's own body structure (i.e. its bending radii) as well as its overall length. This could also inform robotic principles in terms of using the robotic arm's reach envelope as a limiting factor or constraint. Furthermore, fiber self-alignment shown in figure 4 constitutes a significant aspect of fiber-based construction, as the stresses seem to be locally equalized across varying fiber distribution on global scale. This aspect is further discussed in section 3 below.

3 FIBER-BASED DIGITAL FABRICATION

3.1 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.

3.2 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 (Figure 4). Self-alignment of fibroin and sericin as observed in the silk fiber inspired the design of an extruder nozzle, which combines fiber and binder as a single material system.

The extruder nozzle contains multiple outlets laid out in a circular configuration around a single central and larger opening. In this way the HDPE polymer can flow through, before being rapidly solidified by active air-cooling. In this method, the central strand is stabilized by the surrounding thinner strands as well as the outer strands reconnecting to previously extruded strands in close proximity to the overall structure (Rauwendaal 2001). Figure 4 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.

3.3 Synthesis 2: Fiber Placement Tools

In this approach the silkworm cocoon construction is divided into two stages: the first being the parasitic scaffolding and the other being the cocoon construction process itself, as the enclosure within the scaffolding. Fiber-placement in these two phases of the silkworm cocoon construction differs greatly in material quality, organization and function. As the silkworm constructs the scaffolding it "parasites" to its environment, attaching its fibers and pulling it across, connecting to another part of the space repeatedly, building up a three-dimensional web. In the second stage it builds its cocoon in figure-8 pattern, building up wall thickness for the cocoon over time by constantly reconnecting the fibers locally inside the previously built scaffolding.
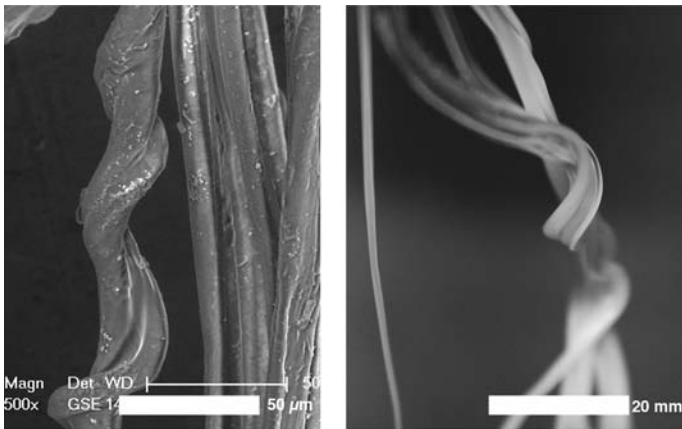
Figure 4. SEM image of silk fibers (top left), HDPE extrusion (top right), and thermoplastic extruder on KUKA robotic arm (bottom).

3.4 Synthesis 3: Parasitical Attachment and Fiber Pulling

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

As seen in Figure 5 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.

3.5 Synthesis 4: Fast Deposition Tool

A secondary end-arm tooling was developed, which is a combination of depositing fiber in controlled speeds while spraying binder onto the fiber. This method also requires a robotic rig and is used in accordance with a previously made scaffolding struc-

ture 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 6) 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 5. Fiber pulling tool (top), fiber pulling tool on KUKA robotic arm with external hook structure (middle), comparison of epoxy resin-soaked polypropylene twine (bottom right) and SEM image of scaffolding silk fiber (bottom left).

The experiments demonstrate that an external structure (equipped here with hooks) is required in order for the robotic tool to "print" with fibers. These works-in-progress demonstrate that it is possible to create fiber-based rigid structures, which may be use 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 vary-

ing properties across its inner wall. The combination of these two processes could lead to a novel and customizable robotic construction process for large-scale fiber-based composite parts.
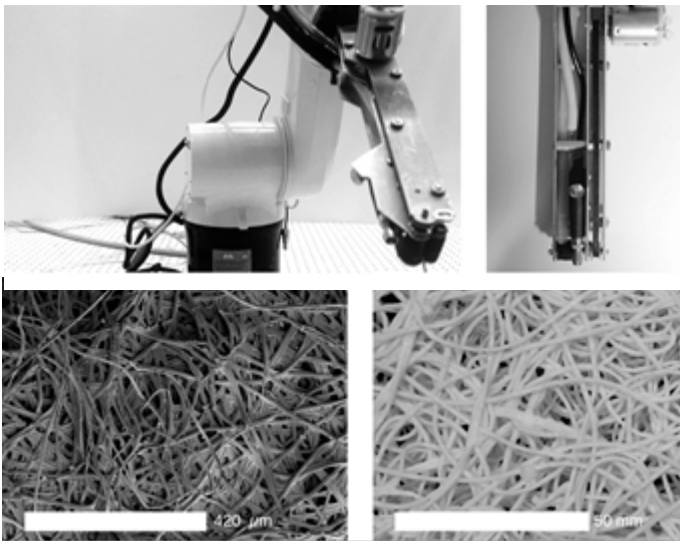

Figure 6. Fast deposition tool on KUKA robotic arm, SEM Image of outer silkworm cocoon surface, composite material from polypropylene twine and contact adhesive.

4 DIGITAL FABRICATION OF FIBER-BASED CONSTRUCTIONS AS A CASE FOR SUSTAINABLE MANUFACTURING: RESULTS, CONCLUSION AND OUTLOOK

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

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

5 ACKNOWLEDGEMENTS

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