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Spinning Smooth and Striated:
Integrated Design and Digital Fabrication of Bio-homeomorphic Structures across Scales

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Abstract

We present a design approach and structural system exploring interrelationships between digitally fabricated tensile membranes and biologically spun fiber-based structures. The approach builds upon from related research into biologically driven design, demonstrating a suite of design tools and techniques for achieving biologically augmented heterogeneous structural systems with spatiotemporal granularity across scales. The structural system is comprised of three sub systems, namely a network of vertical rods, robotically-spun fiber, and biologically-spun fiber. The first acts as a scaffold for the secondary subsystem such that a 3-dimensional tensile fiber structure is constructed and augmented over time via the tertiary subsystem. We coin the term *bio-homeomorphism* to describe structures that present biologically augmented topological isomorphism. The structure is comprised of a 1mX1mX1m cube. Its construction combines robotic winding using a computer-numerically-controlled (CNC) machine with biological spinning using silkworms. The compounded system expresses structural, spatial, and material property variation across scales, mediating the silkworms' behavior. In turn, the deposition of silk informs the spatial configuration of the final structure. The secondary subsystem is digitally fabricated from a single 1-dimensional thread in which material variations that impact silkworm motility and deposition behaviors can be encoded. These can be subsequently decoded through the fabrication process into the final spatial arrangement. The toolpath compensates for rod deflection and enables biological silk spinning to take place; the deposition of silk informs the structure's tensile properties by locally stiffening it. This results in a novel structural typology combining biological and robotic fabrication: 'smooth' and 'striated'.

Keywords: tensegrity, biological design, tensile structure, computational design, robotic winding, insect fabrication, silk.

1. Introduction

In Nature—where shape is cheaper than material—one often finds load-resisting structures that combine multiple systems to accommodate for constantly shifting forces over time. Contrary to traditional manmade structural design—where beams and columns are often composed of homogeneous materials—many natural structures exhibit heterogeneity in both shape and material composition (Hölldobler and Wilson [1]) . Advances in digital fabrication and robotic manufacturing over the past decade have enabled the rapid production of highly customized structural components, yet structural systems in the natural world remain superior in their performance. Design templating techniques have proven to be an interesting approach to interface with biological organisms (Oxman [2]).

We have previously demonstrated that environmental templating can influence a silkworm (*Bombyx mori*) to spin a flat patch of silk instead of a cocoon while still completing metamorphosis (Laucks et al. [3]). These findings culminated in the construction of the Silk Pavilion, a dome made of robotically-spun and biologically-spun fiber that illustrated the potential for collaborative construction across robotic and natural systems. The project laid the foundation for the novel paradigm of a *bio-homeomorphism*, which describes continuous deformation and alteration of a structure, topological space, or geometric object by biological agents, such as silkworms (Moore [4]). The structure must assume, account for, and ideally direct forces generated by the addition of a biological agent.

Bio-homeomorphic structures feature various strategies for conditioning the behavior of the 'agent' that will, in its turn, *condition* the structure. Such structures are comprised of three parts: (1) base structure; (2) template; (3) conditioned structure. Here we introduce a demonstrative example of a bio-homeomorphic structure comprising a CNC-woven tensile fiber construction in combination with silkworms being templated by, and acting upon, the structure.

2. Base Structure

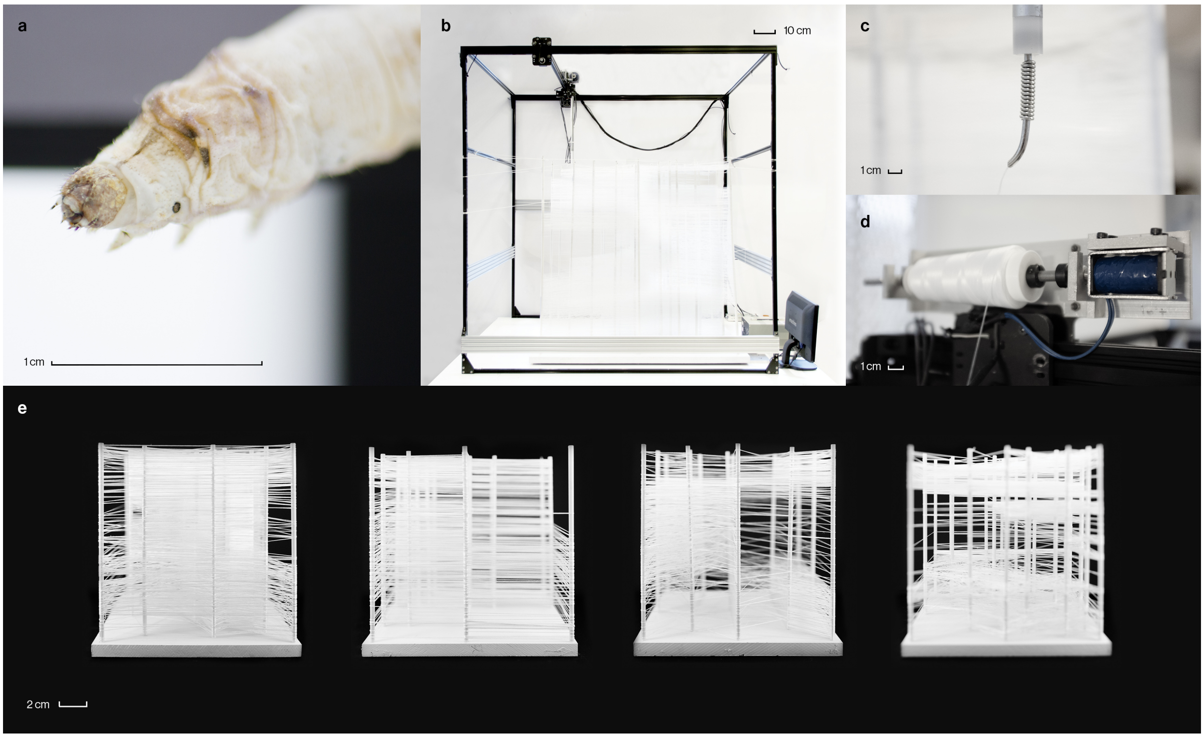

Figure 1: Construction setup and tools. (a) *Bombyx mori* silkworm. (b) Custom gantry with woven structure scale model (1:5) inside. (c) Fiber deposition nozzle. (d) Solenoid tensioning mechanism. (e) 1:33 scale models.

The construction of the base structure is intrinsically tied to the approaches that are implemented to template the silkworms **(Figure 1(a)),** which contribute to the model of the final structure **(Figure 1 (b))**. The base structure is composed of vertical rods around which fiber is woven according to a predefined density distribution. The main fabrication platform consists of a custom CNC machine and a telescoping tubing end-effector to distribute fiber and allows for a greater range on the vertical axis (Z-axis) **(Figure 1 (c))**. The tension of the thread can also be changed on-the-fly with the custom tension adjustment mechanism **(Figure 1 (d)).** The spatial arrangement and geometry can be parametrically designed through varying the distribution of density, layer height, positioning of rod-nodes and layer-wise topology of the toolpath traversals **(Figure 1 (e))**.

3. Templating Strategy

3.1 Geometry

Previous work (Laucks et al. [3]) demonstrates that spatial scaffold arrangements influence the spinning behavior of the silkworms. Here we show that corner angles too, influence the silkworm's spinning pattern. We found that as the angle of two intersecting walls becomes more acute, specifically within the range of 180º to 90º, the likelihood of cocoon formation increases. When the angle of the corners is 150º or greater, silkworms are unable to generate a scaffold for the construction of a cocoon.

3.2 Material

We hypothesized that biological features such as the silkworms' motility and its spinning behavior is altered by the material of the scaffold's thread. A climbing motility assay was designed to quantify the effect of the thread coating material on the silkworm's climbing behavior. Commercial thread (Purely Silk Thread size D) was wound with approximately 1mm spacing between two vertical 15cm stainless steel rods spaced 15cm apart and attached to a polycarbonate base. Single worms, all in the fourth instar stage, were placed upon the bottom of this structure (tail touching base) and allowed to climb upwards until their head touched the polycarbonate. Trials were ended if the path was completed or after 20 minutes elapsed (n=3, 3 alternating trials on each coating). Candidate coatings including Sylgard 184 (Dow Corning), waterproofing aerosol (Scotchgard), and natural beeswax were evaluated based on three criteria: low volatility, minimal odor, and ease of application for use with an automated winding system in a localized manner. White beeswax (Stakich) was selected as the coating and melted onto thread by heating to 64ºC for two minutes and subsequently air drying. We found that silkworms did not complete the path when wax was present in 83% of trials, possibly due to difficulty in grip and stability. For completed trials, the worms climbed on average 3.3 times slower on wax thread than uncoated control. Furthermore, wax appeared to inhibit attachment of biologically-spun silk, suggesting a two-fold functionality of the coating as a negative template for the third subsystem on the second.

Such coatings can be used to create a one-dimensional thread with continuous encoded properties that can be decoded by the fabrication process of the CNC machine (**Figure 2**). In this manner, we are able to predict with more accuracy where the concentration of biologically-spun fiber is likely to be and direct the forces it may generate.

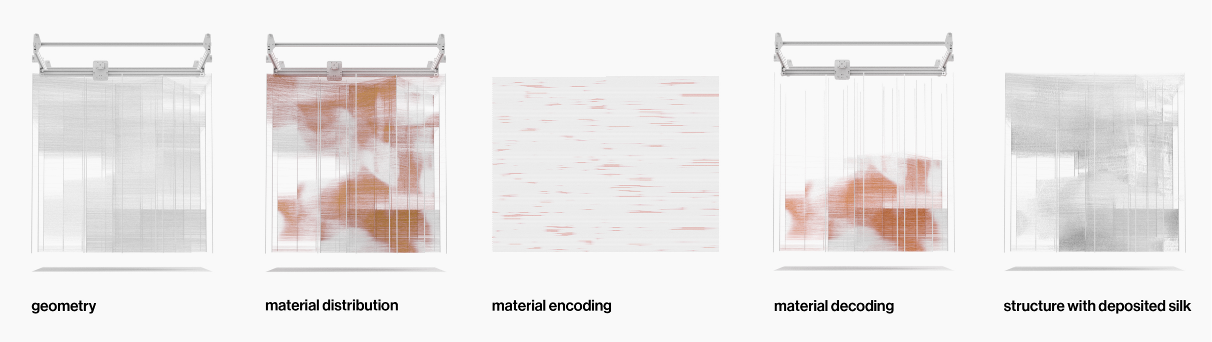

Figure 2: Visualization of the encoded material variation and its decoded form by the fabrication process. Geometry and material distribution of the structure; material variation encoded in the thread and it's unwinding through CNC weaving; structure with deposited silk according to material variation.

4. Conditioned Structure

The silkworms' movement and their deposition—influenced by previous templating methods—will reshape the structure as shown in **Figure 3 (a)**. Previous introduced geometric templating methods can result in flat cocoons where silk fibers displace the elements of the tensile structure by pulling close near-by threads **Figure 3 (b)**. Additionally, we can see a process of "smoothing" a hard corner into a Bezier-like curve **(Figure 3 (c))**.

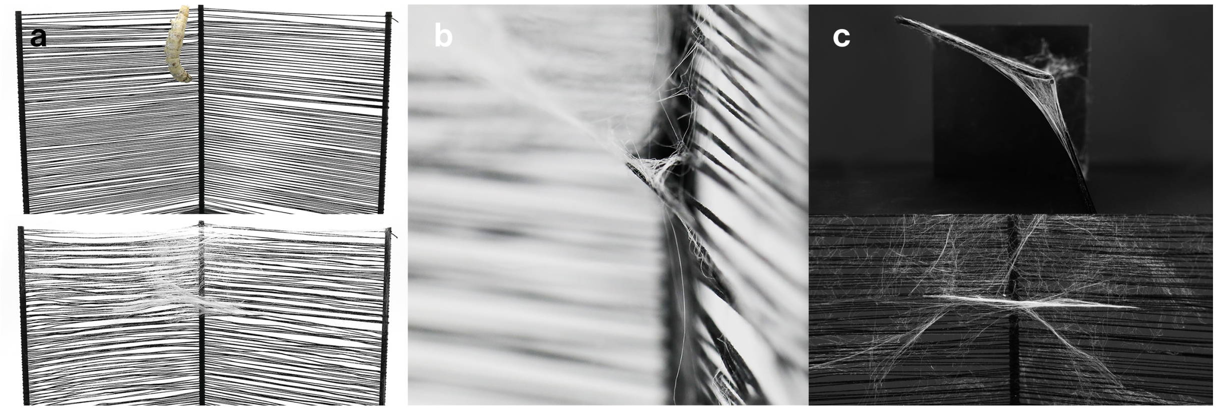

Figure 3: Experiments showing silkworm alteration of the base structure. (a) Initial tensioned fiber structure shown on the top and resulting alteration is shown on the bottom; (b) detailed view of pulling of threads by silk worm deposited silk. (c) Smoothing of the corner angles through fiber deposition of the silk worms.

5. Conclusion

We have introduced the concept and demonstrated the implementation of a prototype bio-homeomorphic structure. The term *bio-homeomorphism* is used to characterize the structure for it follows this sequence: (1) design of a scaffold with properties responsible to condition a biological agent (in our case the silkworm); (2) conditioned movement of the organism within the structure and (3) deformation by addition of material (natural silk); and finally, (4) the alteration of the original scaffold that completes the final structure.

Acknowledgements

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References

[1] B. K. Hölldobler and E. O. Wilson. "Weaver Ants," *Scientific American,* vol. 237, pp. 146-155, Dec. 1977.

[2] N. Oxman. "Templating Design for Biology and Biology for Design," Architectural Design, Special Issue: Material Synthesis: Fusign the Physical and the Computational, Volume 85, Issue 5, Pp. 100-107, Sep./Oct. 2015

[3] N. Oxman, J. Laucks, M. Kayser, J. Duro-Royo, C. Gonzales-Uribe. "Silk Pavilion: A Case Study in Fiber-based Digital Fabrication," *FABRICATE Conference Proceedings*, pp. 248-255.

[4] G. H. Moore. "The evolution of the concept of homeomorphism," *Historia Mathematica*, vol. 34, 3, pp. 333-343, Aug. 2007.