Biological Computation for Digital Design and Fabrication

A biologically-informed finite element approach to structural performance and material optimization of robotically deposited fibre structures

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Abstract. *The formation of non-woven fibre structures generated by the Bombyx mori silkworm is explored as a computational approach for shape and material optimization. Biological case studies are presented and a design approach for the use of silkworms as entities that can "compute" fibrous material organization is given in the context of an architectural design installation. We demonstrate that in the absence of vertical axes the silkworm can spin flat silk patches of variable shape and density. We present experiments suggesting sufficient correlation between topographical surface features, spinning geometry and fibre density. The research represents a scalable approach for optimization-driven fibre-based structural design and suggests a biology-driven strategy for material computation.*
Keywords. *Biologically computed digital fabrication; robotic fabrication; finite element analysis; optimization; CNC weaving.*

INTRODUCTION

Form-generation and Optimization in Nature

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

Form-generation and Optimization in *Digital Design*

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

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

BACKGROUND

Biological Computation for Digital Design and Fabrication

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

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

The Silk Pavilion – General Background

Inspired by optimization processes in Nature like that of the slime mold described above, the *Silk Pavilion* is an architectural structure fabricated by digital fabrication technologies combined with the deployment of live silkworms. It explored the relationship between digital and biological fabrication on product and architectural scales. The *primary structure* is created of 26 polygonal panels made of silk threads laid down by a CNC (Computer-Numerically Controlled) machine. Inspired by the silkworm's ability to generate a 3D cocoon out of a single multi-property silk thread (1km in length), the overall geometry of the pavilion is created using an algorithm that assigns a single continuous thread across patches providing various degrees of density. Overall density variation is informed by the silkworm itself deployed as a biological "printer" in the creation of the *secondary structure*. A swarm of 6500 silkworms were positioned at the bottom rim of the

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

scaffold spinning flat non-woven silk patches as they fill the gaps across the CNC deposited silk fi bres. Following their pupation stage the silkworms are removed. Resulting moths can produce 1.5 million eggs with the potential of constructing up to 250 additional pavilions (Figure 1).

Affected by spatial and environmental conditions such as geometrical density and variation in natural light and heat the silkworms were found to migrate to denser and darker areas. Desired light effects informed variations in material organization across the surface area of the structure. A season-specific sun path diagram mapping solar trajectories in the space dictated the location, size and density of apertures within the structure in order to lock in rays of natural light entering the pavilion from South and East elevations. The central oculus is located against the East elevation and may be used as a sun-clock.

The construction process of the *Silk Pavilion* was inspired by *basic research experiments* reported herein that informed processes of modeling, analysis and fabrication. This paper reports upon experimental work considering biological forms of computation for digital design modeling, analysis and fabrication. Specifically, we explored the formation of non-woven fi bre structures generated by the *Bombyx mori* silkworm as a computational schema for determining shape and material optimization of fibre-based surface structures. This biological form of "computation" can potentially exclude the need for Finite Element methods.

AIMS AND GOALS

Fibre-based structures are ubiquitous in both architectural and biological systems. Robust structural performance involves the balancing of force-and-response in order to achieve material morphologies that are structurally efficient and environmentally effective (Oxman, Tsai et al. 2012). Typically this process involves a step-wise process including computational modeling, fi nite-element analysis and digital fabrication. Biological fibre-based structures such as the silkworm's cocoon however may provide for the unification of these three media through the use of the silkworm's path as an optimization "tool path" and a fabrication "technology". The guiding assumption here is that the silkworm's ability to generate fi bre structures with varying degrees of density based on its environment has been perfected through evolutionary pressure. We also assume that the cocoon is an optimal structure which itself is based on the idea that optimization-seeking

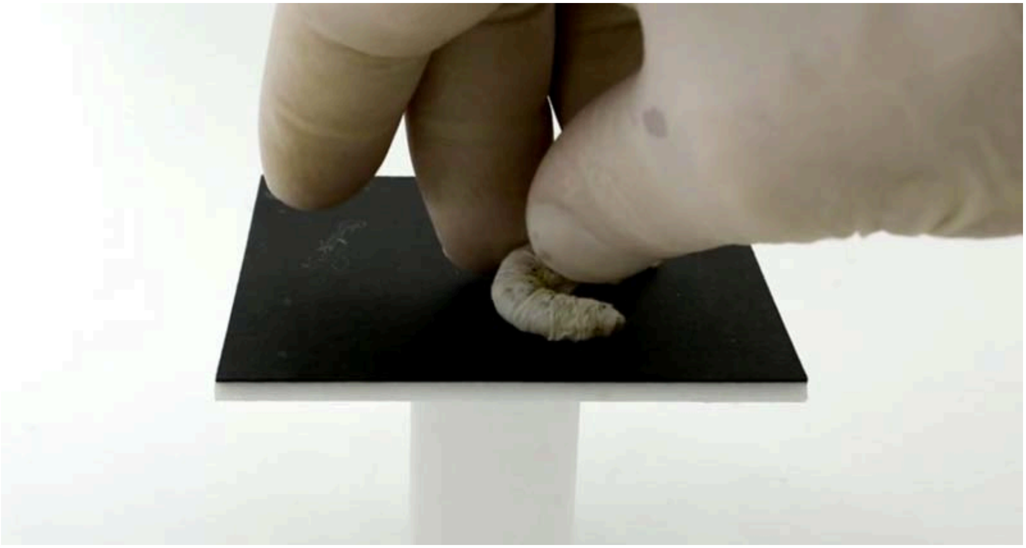


Figure 2
Placement of a Bombyx mori silkworm on top of a flat surface-spinning platform.

processes are omnipresent in Nature. Having been developed without top-down control this case may represent a scalable approach for fibre-based structural design based on optimization. Our main goal is to determine whether these structures are likely to yield reasonably efficient solutions to combinatorial optimization challenges such as load informed fibre-density distribution in membrane structure.

METHODOLOGY AND EXPERIMENTAL SET-UP

The experimental set-up consisted of a series of surface patches measuring 80X80mm in surface area with varying sectional configurations. A live silkworm was positioned on top of the surface and left to spin. We hypothesized that spinning configurations and fibre density distribution would vary according to the morphological features of the "hosting environment" (Figure 2).

Initial Experimentation to Determine Fibre-Density Variation in Flat-spun Silk

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

The Dice Series

Following, we began introducing a central vertical axis of varying heights to determine (1) at which height point would the 3D cocoon structure emerge, and (2) how might fibre distribution be affected by the relative location of the vertical axis and its height. A family of tent-like structures consisting of a rectangular surface patch with a single vertical axis ("1-dice section" per Figure 4) was set up.

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

The experiments demonstrated the following: (1) a 3D cocoon structure emerged only at a sectional height of 21mm height below which a tent-like structure in the form of a rectangular pyramid was

Figure 3
A Bombyx mori silkworm completing the deposition of approximately 1km of flat-spun silk. The research confirms that given the absence of a vertical axis the silkworm will spin a flat silk patch.

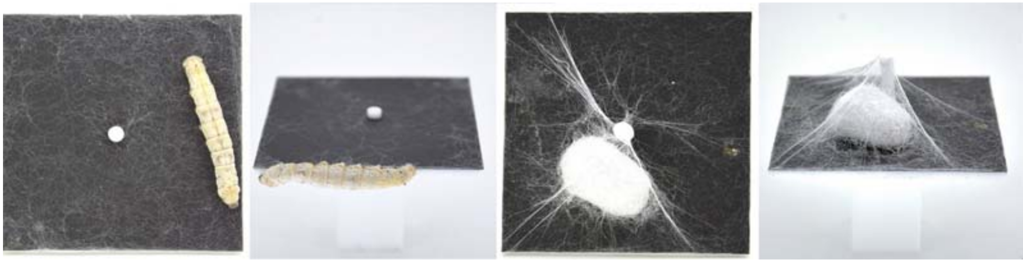


Figure 4
Comparison of two 1-dice configurations with a 3mm and a 21mm vertical axis illustrating the difference between flat spinning (sufficiently short vertical axis) and a cocoon spinning (sufficiently long vertical axis).

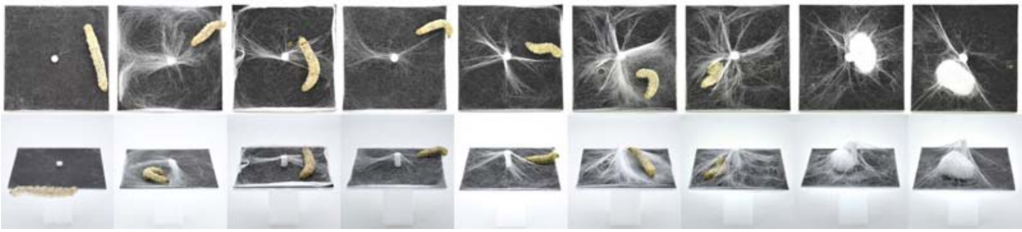


Figure 5
Series of one-dice platforms ranging in vertical axis height from 3mm to 27mm each with 3mm increments.

spun. Given the dimensions of the natural cocoon we assume that a minimum height of ~21mm accounting for the longitudinal axis of the cocoon must be provided in order for a 3D structure to emerge. In the absence of this height, a non-enclosed surface patch will be spun; (2) fibre density typically varied as a function of the distance from the central vertical pole to the surface boundary. This may point to a local optima condition requiring the least amount of energy for the construction of a strong stable structure within a given timeframe (Figure 6); (3) boundary contours were typically denser. We assume this is

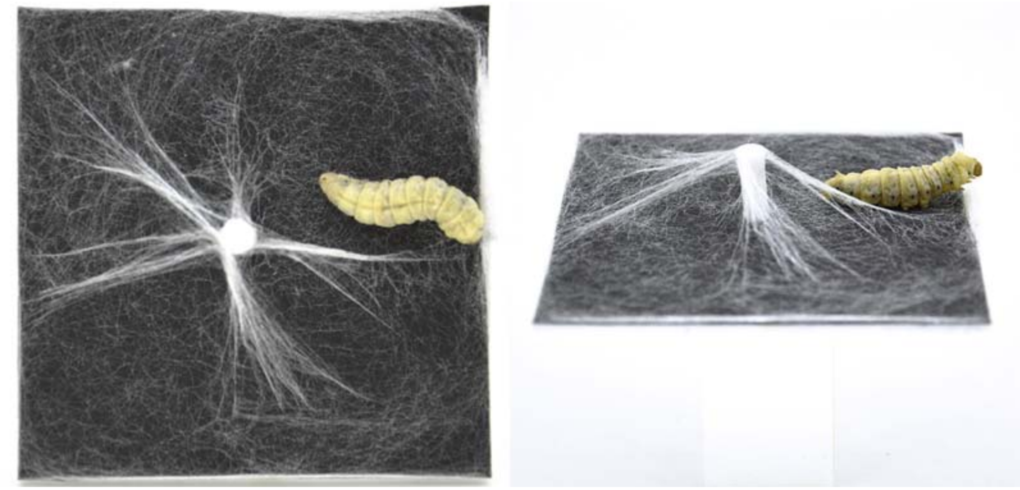


Figure 6
18mm one-dice platforms illustrating higher density deposition along the shortest distances from the geometrical center to the surface boundary contour.

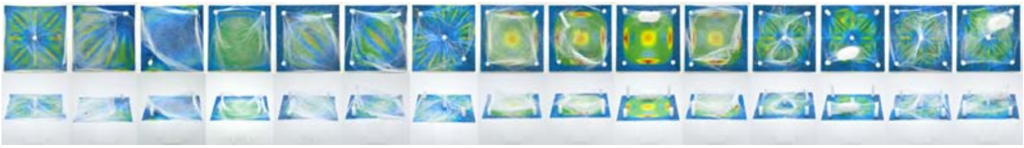


Figure 7
Series of (15) rectangular FEM-dice platforms ranging from 10mm to 15mm in pole heights.

due to the silkworm's constant search for a vertical pole tall enough to allow for cocoon construction.

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

The Rectangular FEM-Dice Series

The series included a set of 15 flat 80X80mm surface patches in different dice-face configurations. Poles of 10-15mm height were used to define the planar confirgruation and the sectional hiehgt of the patch (Figure 8). A live silkworm was then positioned in each patch to spin a typical 1km long filament. The assumption was that the variation in fibre density and organization would reflect the morpolohgical constrains given by the "environment" (i.e. the sirface patch).

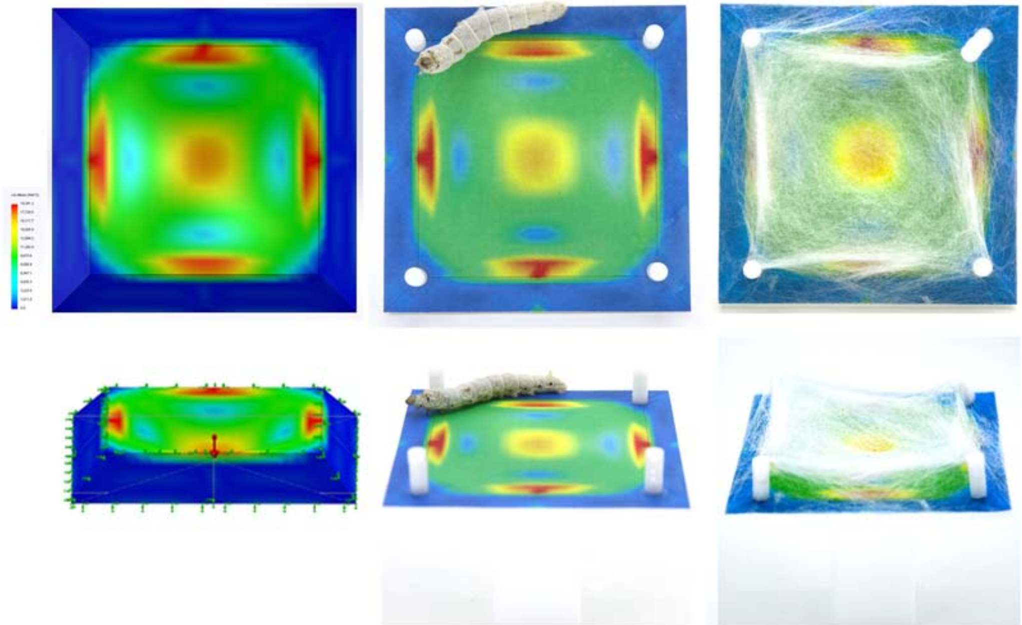
FEM representations were computed as hypothetical static-force studies for anticipated fibre variation in a membrane tent-like structure accomodating the environment given by the patch. Linear Elastic Isotropic 101 Nylon with an elastic modulus of 1000000000 N/M^2 was used to represent the membrrane material. The results of the study confirm general correlation between anticipated Stress-Strain calculations (computed using the SolidWroks environment) and the resulting fibre-structure as spun by *bombyx mory* silkworm. See a typical example in Figure 8.

The Polygonal FEM-Dice Series

This series is analogous to the previous one (FEM-Dice Series) containing four models based on a polygonal patch as the base environment (Figure 9).

The results of the study confirm general correlation between anticipated Stress-Strain calculations (using the SolidWroks environment) and the

Figure 8
4-Dice face configurations. L to R: Digital representation of anticipated stress for membrane structure based on 4 poles calculated within SolidWorks; physical model with digital representation as base. The silkworm is shown to the right; physical model juxtaposed with silk fibre by the Bombyx mori silkworm. Denser fibres appear between poles along boundaries as anticipated by the FEM model.



resulting fi bre-structure as spun by bombyx mory silkworm. See a typical example in Figure 10 below demonstrating fi bre distribution along regions of highest stress around the central vertical axis of the patch 10.

The Thrust Vault Series

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

The assumption was that the variation in fi bre density and organization would reflect the morpolohgical constraitns given by the environment. Indeed, our results confirm this correlation below 20mm height (above this heigh the 3D cocoon appeared): a typical model demosntrates increased fibre density along the boundaries. In addition, a circula patch appears at the center of the patch marking the silkwrm's attempt to form a 3D cocoon between the two planes that make up the section (Figure 12).

The Maltese-cross Series

The final series introduces variations in both plan and sectional configurations. The plan configuration in this series is no longer constraint to a completely flat rectangular, polygonal or circular surface patch but rather it is oriented in a Maltese-cross configuration. The variation in section height introduces spatial 'gaps' to the silkworm's movement as it spins its silk in circular motion. Sectional height varies between 5mm and 20mm with 5mm increments; each model is repeated twice to validate the consistency of the resulting morphology. Colour annotations represent variation in curvature with the colour green typically representing anticlastic curvature and blue repre-

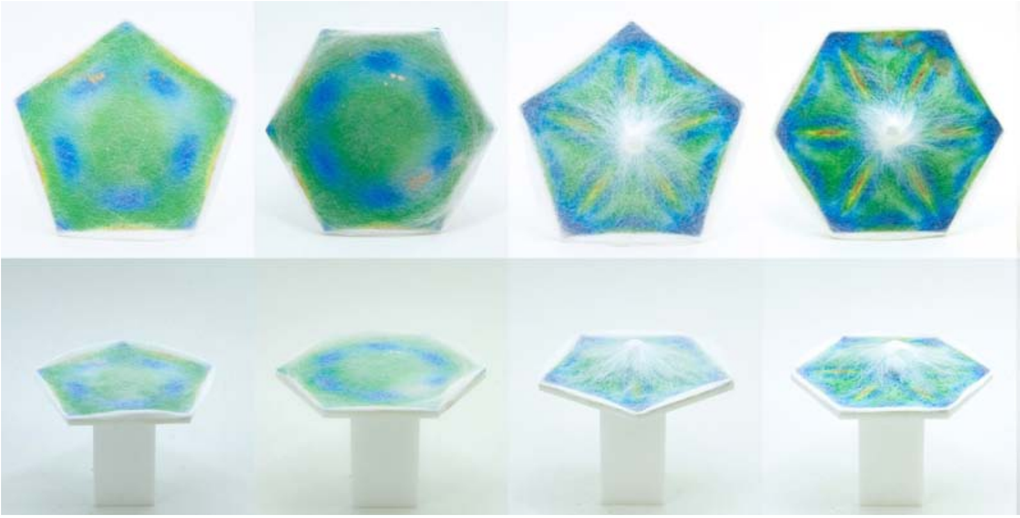


Figure 9
Series of polygonal FEM-Dice platforms.

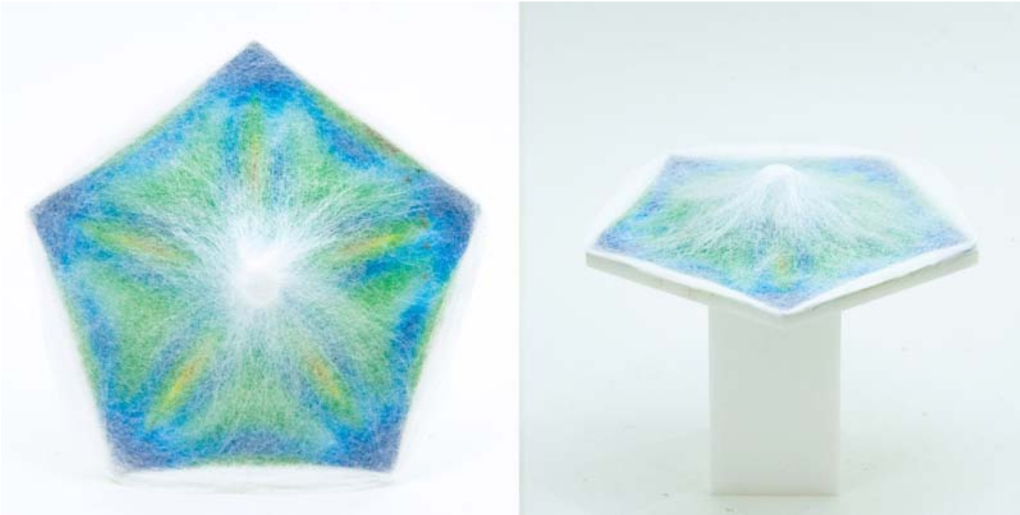


Figure 10
One-dice polygonal platforms showing greater density of silk deposition in areas of higher Stress-Strain.

senting synclastic curvature (Figure 13).

As anticipated, the results reflect the correlation between fibre density and surface features demonstrating a combination between the flat-dice-series and the thrust-vault series.

RESULTS AND DISCUSSION

In this paper we have shown that the silkworm *Bombyx mori* forms fibrous silk networks on flat patches. Fibre density distribution appears to be sufficiently similar to the anticipated fibre density variation that was computationally generated for a prescribed

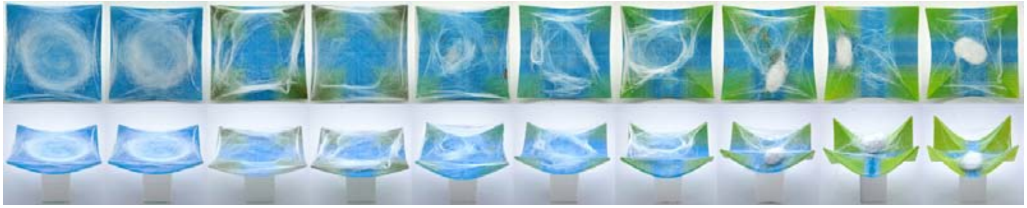


Figure 11
Series of three-dimensional thrust vault spinning platforms.

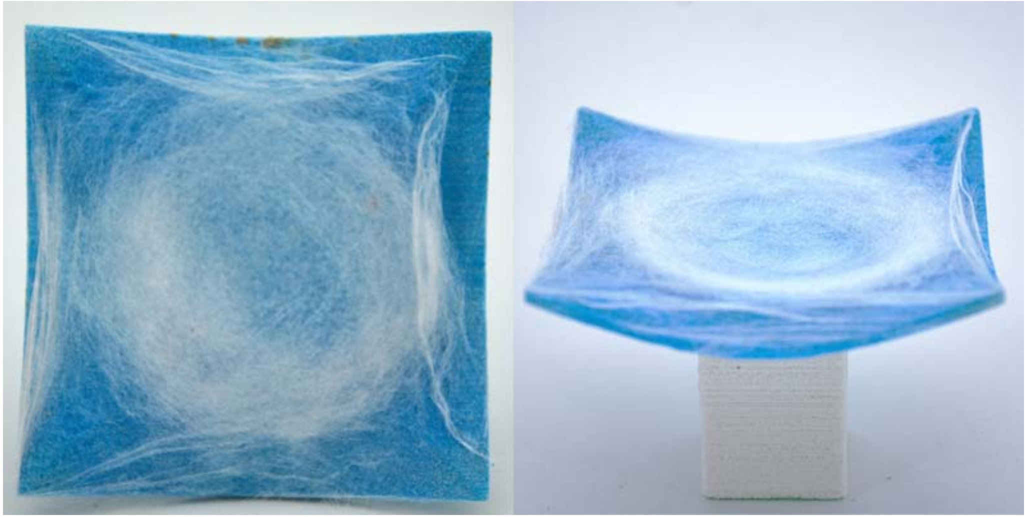


Figure 12
20mm tall thrust vault spinning platform demonstrating the silkworm's spinning behavior.

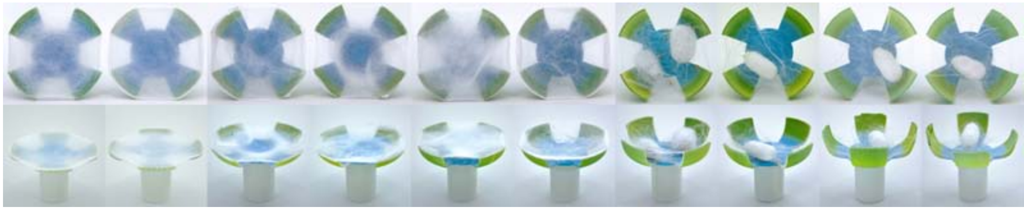


Figure 13
Series of three-dimensional Maltese-cross spinning platforms.

membrane structure of the same mass and surface area. We conclude that the *Bombyx mori* silkworm itself may be used as a biological "tool" with which to "compute" fibre distribution within small-scale 1:1 structures, or as scaled representations of larger architectural structures constructed with fibrous materials.

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

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

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