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Adaptable Meshes: A Dynamic Approach to the Construction of Membranes

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Abstract
The fabrication of thread-based membranes and panels is typically constrained by the limitations of the underlying scaffold in which it is constructed. In this paper we present an alternative method of developing fiber-based meshes that are the result of ongoing research with the *Bombyx mori* silkworm done by the group and explored previously [1][2]. It consists of a system that uses a heat bonding thread comprised of a polyester core coated in PLA that is deposited by a custom end effector responsible for laying the thread and creating anchor points by heating up and fusing the threads together. This research shows how we can reduce the complexity of the scaffold while increasing the ability to create anchor points within the mesh itself, allowing for a more intricate and adaptable behavior of the system. In this paper we present (1) the mechanism and development of the end effector; (2) the approach for toolpath pre-planning; (3) future steps for the inclusion of a feedback loop capable of interfacing with living organisms.

Keywords: membrane design, thread-based fabrication, biological design, computational design, fabrication system, tool design.

1. Introduction
Within the last five years, the construction of robotically spun meshes has been actively explored as means of controlling fiber distribution on membrane structures, allowing for structural optimization and aesthetic control and curation. Although recent examples [2][3] have successfully demonstrated that the process yields promising results in both structural and architectural realms, designers and engineers still have to conform to the boundaries of fairly limited fabrication mechanisms.

The constraints imposed by (a) the end effector chosen to spin the fiber and (b) the support (i.e. frame) in which the spinning process will occur have a major influence on the possibilities for the development of the toolpath. That is because the current approaches have relied on the spinning process to be done around pre-defined anchor points at the edges of the supporting frame without the possibility of having intermediate anchors within the boundaries of the support which, in its turn, becomes more complex.

Here the authors present a novel approach to the development of membranes which introduces intermediate connections along the surface of the membrane. The process is made possible by the development of a custom end-effector responsible for creating such connections and depositing the yarn that forms the mesh, coupled with a toolpath generation method that allows for the simulation of what the membrane will look like. Furthermore, we propose future steps that aim to implement a feedback loop in which the system will be able to (a) accommodate for any changes resulting from the spinning process and (b) adapt to the addition of living organisms for a combined mesh.

2. End-Effector

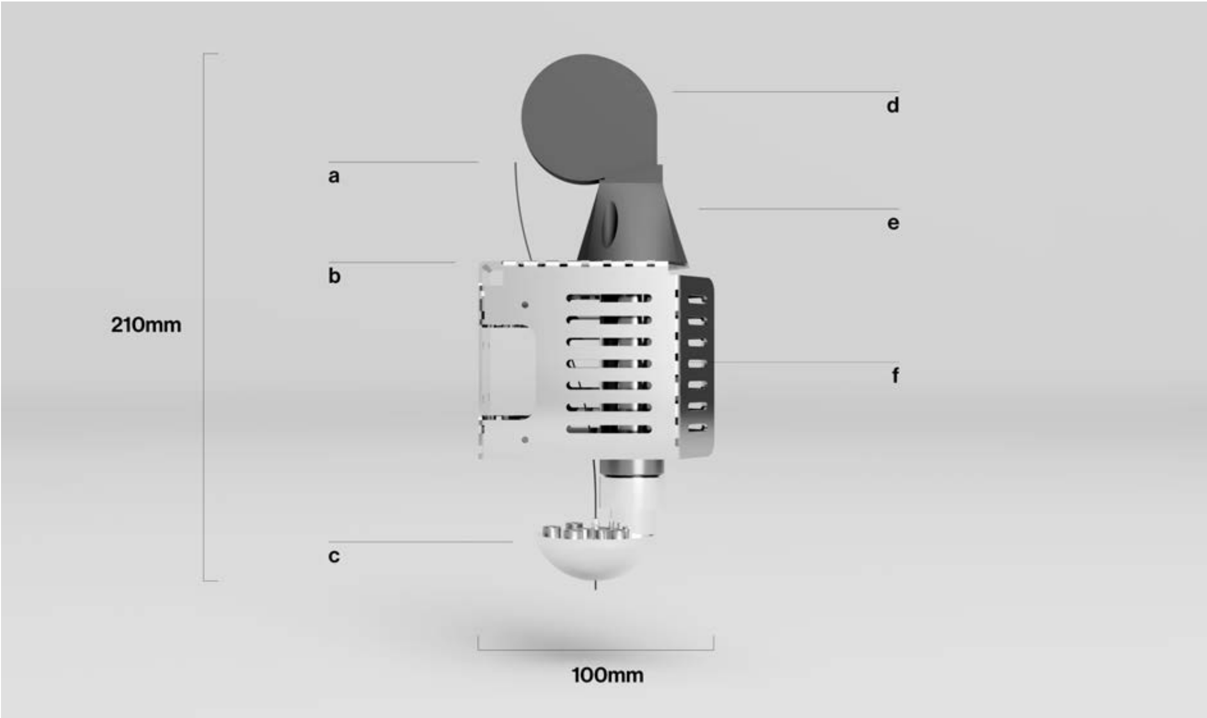

Figure 1: Render of the end-effector and its components. (a) Heat-bonding thread; (b) Stainless steel guard; (c) Aluminum nozzle; (d) Fan; (e) Fan Adapter; (f) Heater.

The custom end-effector can be attached to fabrication systems such as CNC machines or robotic arms. It is responsible for heating up the PLA coating of the thread and fusing it to previously laid out thread, therefore creating connection points. The tool is designed to be in a constant "on" state–meaning it is always heating up the thread–allowing for connections to be made at any stage of the fabrication and releasing the necessity of having to track where existing threads are in order to fuse them together.

2.1. Mechanism

The end-effector works by creating an air flow that starts at the top of the tool, with a 12V fan (**Figure 1(d)**) that goes into the heater (**Figure 1 (f)**) and finally exits through the nozzle (**Figure 1(c)**) where it meets the heat-bonding thread.

The heater consists of spooled nichrome wire that spirals around a ceramic core and is covered by a steel shell. This allows for the cold air flow to pass through and carry the heat over to the nozzle. The ceramic core also houses a thermocouple probe that allows for a feedback control of the temperature. The heating element and thermocouple are controlled by a microcontroller that gives the user access to the temperature control.

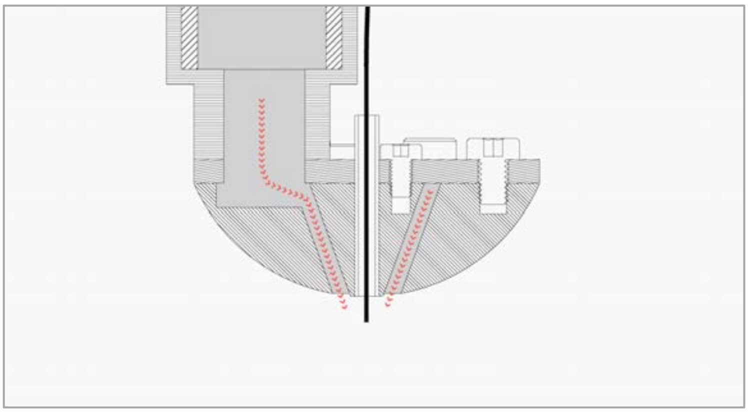

Figure 2: Section view of the nozzle. The red arrows indicate the air flow within the nozzle.

A dome-shaped nozzle is used, allowing the tool to smoothly go over existing threads on the mesh, in any direction these may come from. Since the nozzle is made out of aluminum, its body also gets warm with a thermal focal point where the air exits the nozzle and meets the thread (**Figure 2**).

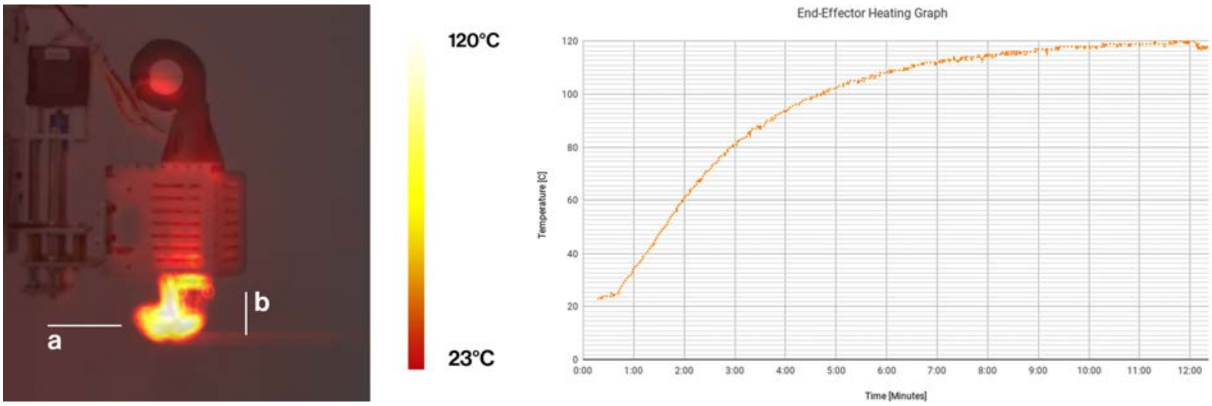

Figure 3: IR heatmap showing heat distribution on nozzle (a) and thread (b). Graph (right) shows heating curve of End-Effector at room temperature.

Due to the thermal inertia of nozzle body, the full target temperature of the nozzle is reached after approximately 11 minutes (**Figure 3**), using 188.6 Watts at a room temperature (22-23°C). However, the heating element and fan already produce a stream of approximately 80°C after 15-20 seconds and the application temperature of the PLA coating (minimum of 120°C) is reached at approx. 4-5 minutes, allowing for displacement of the end-effector and operation of the robotic environment it is mounted in.

PLA coated thread is deposited at a temperature of 120°C (**Figure 3(a)**). The thermal inertia and radiation of the metal nozzle body result in a pre-heating of already deposited thread around the focal point in which new thread is placed.

2.2. Setup and Operation

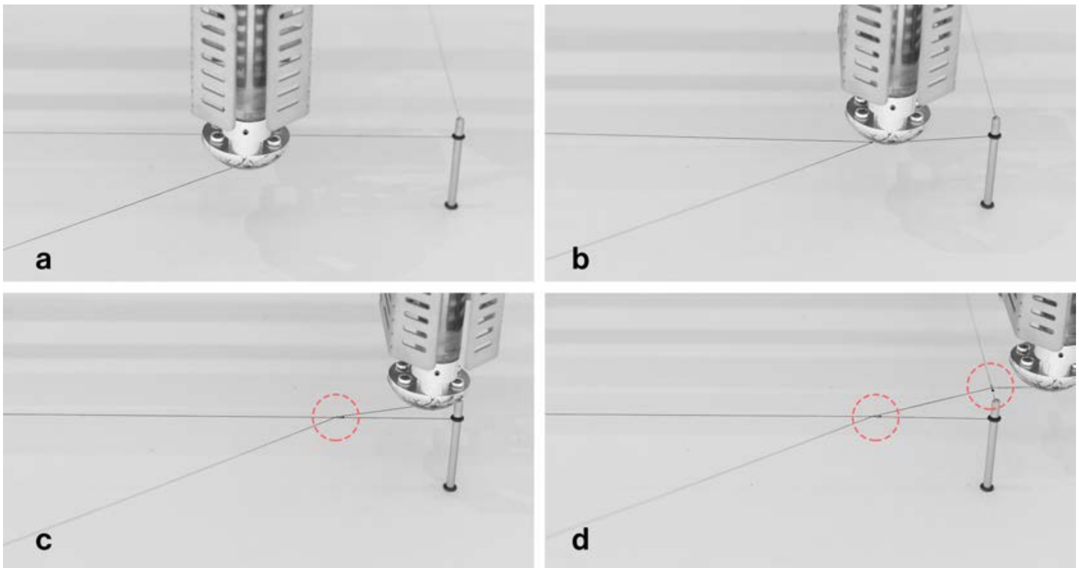

Figure 4: Image sequence showing the creation of two anchor points on a thread frame.

The setup necessary for the system to work is minimal: an outline of the desired membranes created with the heat-bonding thread. The initial shape of the membrane will define the boundaries of the workspace and, within these limits, the anchor points can be created. When compared to previous approaches for fiber-based membranes [2][3] the frames are considerably simplified since the anchor points do not need to be defined beforehand. In the event of a construction of multiple panels with different meshes but same outline this would prove to be an advantage in the fabrication of the modules.

In order to simplify and exhibit the basic behavior of the system, we have used a 300mm x 300mm outline. The sides of the square (made out of heat-bonding thread) were attached to short steel poles that secured the initial setup.

An example of anchor point creation can be seen on **Figure 4**. With the tool starting outside the boundaries of the membrane (**Figure 4(a)**) it crosses one of the sides (**Figure 4(b)**) and fuses the existing thread to the *operation thread* (the thread being fed through the end-effector), creating a first anchor point (**Figure 4(c)**). From that point onwards, every time the operation thread goes over an existing thread it will create a new anchor point (**Figure 4(d)**). With time, the greater the number of existing threads and anchors, the greater is the possibility of creating new connection points.

3. Toolpath Planning and Simulation

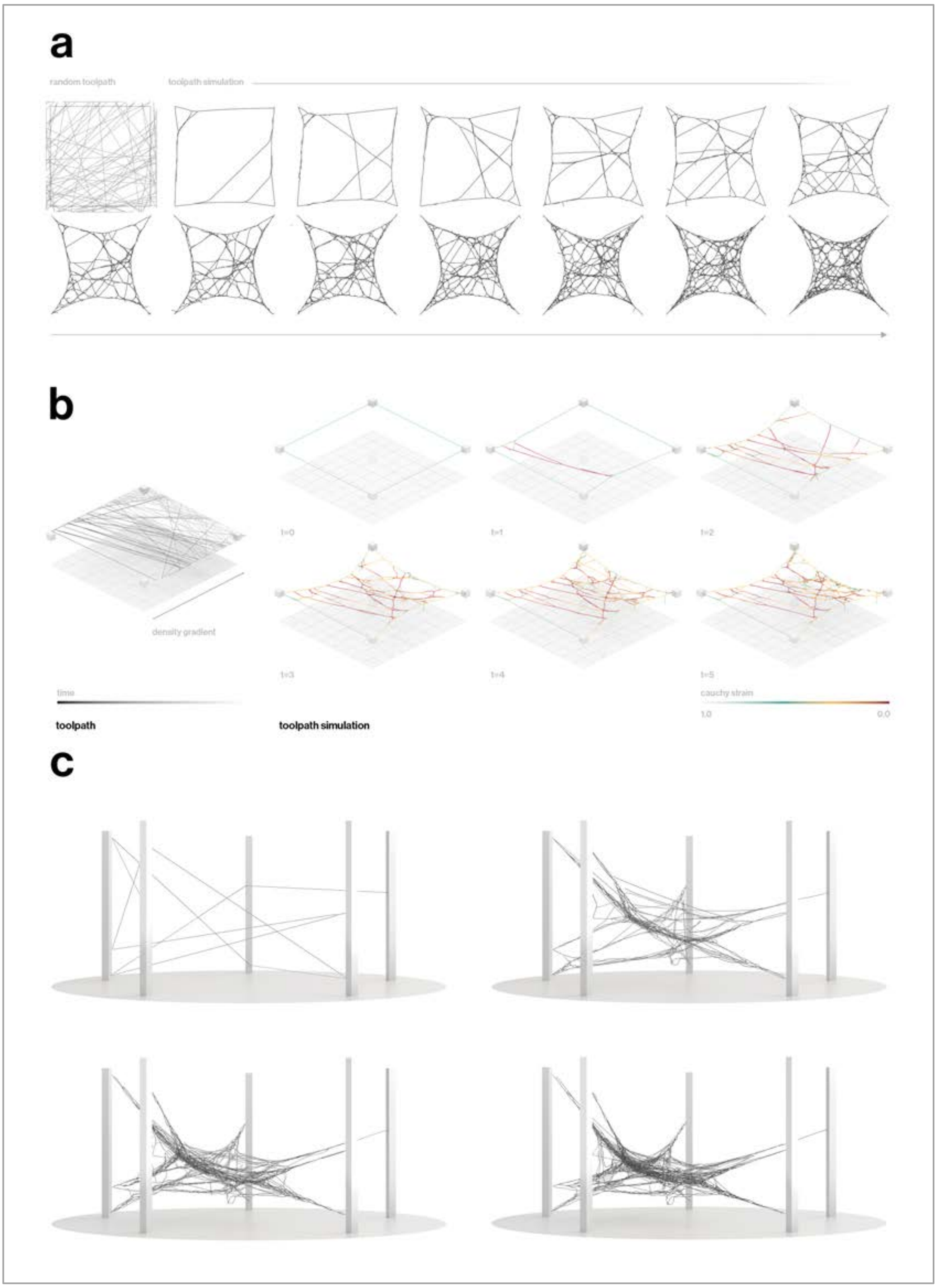

Figure 5: (a) Top view of random toolpath and simulation of intermediate anchor points along time. (b) Deformation and stress variation on the mesh over time. (c) Example of three dimensional membrane application.

Path planning and simulation must work in parallel when utilizing the tool presented here. Similar to CAM software, the visualization of the path itself does not reflect the outcome of the process and therefore a simulation tool was developed.

A basic random toolpath (**Figure 5(a)**) consists of straight lines and does not display the changes the mesh will suffer over time. Factors such as the number of times it goes over the threads, angle of incidence, proximity of anchor points and stress on the anchor points will affect the rate of creating successful connections. Thus the simulation tool, at this stage, is not a perfect prediction of the outcome but works as a guiding tool for displaying an overall density distribution.

It is also important to observe that missing connections and overstress of anchor points (**Figure 5(b)**) are the main cause for loose threads and can be avoided by having (1) constant thread management in order to prevent it from creating slack and (2) increasing the chances of creating connections by moving the end-effector perpendicular to existing threads. Stress reduction can also be achieved by increasing the number of anchor points that will distribute the force within the mesh.

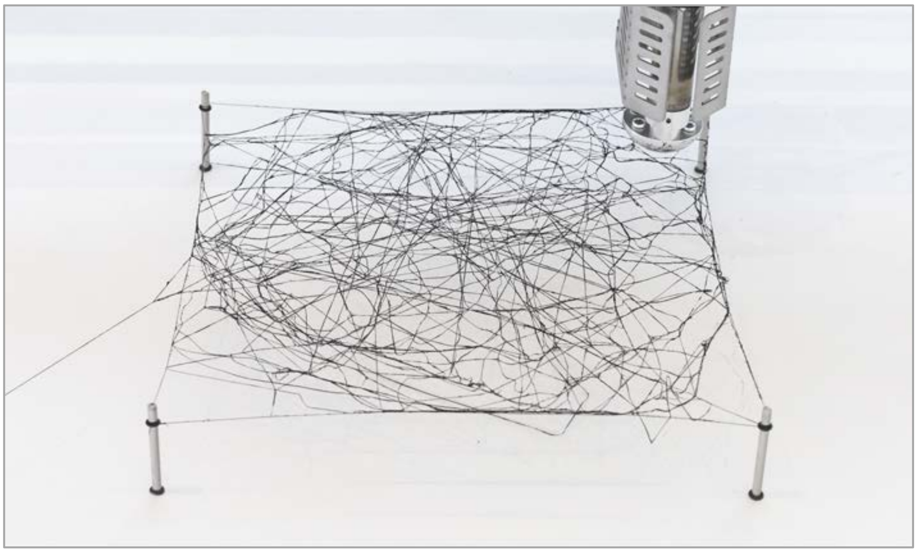

Figure 6: Example of 300mm x 300mm flat mesh.

4. Feedback Loop and Future Steps

Although at the present state the system works mostly as a pre-planned fabrication approach, it offers multiple research directions that can further explore its inherent qualities. The group has been looking into establishing a feedback look with cameras and IR sensors that will enhance the flexibility provided by the tool and path planning.

For instance, one could use this setup not as a means of executing a predefined plan but rather as an on-the-fly-mechanism that is able to "see" what is being created and act based on it. At a first glance, this could be seen as a loss of control on the design of the membrane but, on the other hand, may yield interesting results if guided by a set of rules that allows for the appearance of an emergent behavior and autonomy of the system [4].

Furthermore, we can think of adding new agents to the system that will enhance the autonomy of the system and its flexible character. For instance, the addition of silkworms to the system would provide an interesting factor of unpredictability, "forcing" the machine to adapt the path in order to accommodate and allow for silk deposition which would, in its turn, reinforce the membrane in specific places. Because the system does not have to rely on specific anchor points, it is able to adjust to the organisms' behavior and create, for example, a path for it to walk on making it as dense or sparse as needed, based on the number of connections it makes.

4. Conclusion

The system and tool presented in this paper can be seen as a step towards an ideal adaptable approach for fabrication of meshes. It suggests that, in order for that to be truly attained, compromises need to be made in the amount of control designers have over the outcome of the process–it does require tools that support this kind of design process but also calls for a change in the way we perceive our interference in the process itself.

That said, it offers a novel form of fabricating membranes in a dynamic manner, one that can adapt to different stimuli from the environment or other additional agents. It is still being explored in a larger scale but has yielded promising results so far which leads us to believe that it can soon be applied in the construction of a larger pavilion-scale structure.

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