CNSILK

Spider-Silk inspired Robotic Fabrication of Woven Habitats

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Abstract. Spiders create sophisticated silk web-structures by varying morphological composition, material make-up, and organizational logic of their silk threads. CNSILK explores the nexus of digital fabrication and biomimetic design through the creation of fibers inspired by the silk created by *Aranaeid* spiders. It seeks to achieve woven architectural structures without seams that are continuous in morphology and physical property through the implementation of a multi-axes tensile digital fabrication platform. Recent proof-of-concept tests focus on the use of a robot arm to test weaving capabilities through unique end arm tooling and, in parallel, the development of a larger scale proof of concept on the overall proliferation of the material system given geometrical constraints.
Keywords. Robotic weaving; biomimetic fabrication; woven habitats; robotic construction; tensile printing.

Introduction

Robotic fabrication and manufacturing technologies are traditionally known for their benefits in automation processes of full-scale design and construction. However, their value as design content and material generators has only recently been explored. This research aims to explore the potential of integrating advanced robotic manufacturing techniques through custom developed end-arm tooling with biologically inspired design principles to create a biologically inspired digital design fabrication platform. With a special focus on robotic deposition of tensile fibers inspired by spider silk generation and construction, this design approach seeks to establish a pilot case study in biomimetic fabrication. By integrating on-the-fly material generation, multi-axes fiber control, and a seamless assembly method, the platform described herein seeks to mimic natural construction methods while considering material repercussions relevant to architectural construction scales. Transcending its utilitarian role merely as a construction automation technology, the research establishes a novel approach to robotic fabrication considering its shift from a design representation and materialization tool (i.e. prototyping) to a design generation platform.

Biomimetic Inspiration

Of all known silk producing insects and animals, spiders make the most extensive use of silk with many types of spider silk playing a major mechanical role among other functions (Zhao, Feng, Yu, Cui, and Zou, 2005). When examined under high magnification, the structure of orb-web spider silk is surprisingly complex (Figure 1). The architecture of a spider web is determined by the constraints of the spider's environment as well as its energy balance. The structural integrity of an orb-web, for example, is dependent on the surrounding objects (i.e. branches and leaves) to which it is attached. Larger webs will be likely to catch more prey, but the web material must be structurally optimized given the high metabolic cost of spinning silk (Gosline, DeMonet and Denny, 2004). In the process of spinning a complete web, spiders vary not only the physical structure of the web, including its morphological features such as density, relative thickness and organization, but also its material composition.

From the perspective of digital design fabrication, spider web spinning represents a form of natural additive manufacturing not unlike multi-material 3-d printing in which the end product is informed by multiple environmental factors and material optimization (Oxman, 2010). In contrast to industrial additive manufacturing methods, which generally print with compressive elements, spider webs are composed of largely tensile elements resulting in seamless structures with functionally graded material compositions.

Methods & Progress

This research explores the various possibilities and potential for weaving on a robotic platform with a focus on the creation of unique geometries and material properties introduced through variations in robotic tool-paths. This process implies the integration of material generation as part of the fabrication process, seeking to weave with fibers synthesized immediately prior to deposition.

Experiments were conducted using three general types of materials. Initial tests were done with the robotic arm (KUKA KR5 sixx R850 industrial 6-axis robotic arm) using 4-ply cotton yarn wrapped on to a steel frame structure. Further experiments were conducted by weaving with nylon 6,6 synthesized and drawn from the interface of a two-phase system.

Yarn Weaving

Four-ply cotton yarn was used as the weaving material and a galvanized steel frame with hooks spaced 0.0508 m by 0.706 m was used as a weaving frame (Figure 2). A holder attachment to the arm was built to contain a spool of yarn; to allow the relatively bulky holder to maneuver around the pegs, the yarn was passed through a 0.05 m long hollow tube attached to the distal tip of the holder relative to the robotic arm.

Nylon 6,6 Synthesis

Nylon 6, 6, was synthesized from adipic acid and hexamethylenediamine solutions. A 10% w/v solution of hexamethylenediamene (98%, H11696) in water with 1% w/v NaOH (reagent grade >=98%, S5881) and a 10% w/v solution of adipoyl chloride (98%, 165212) in Hexane was used. This reaction occurs at the interface between the two solutions and, if the product (nylon) is continuously removed from the interface, the reaction is driven forward, resulting in a single strand of nylon.

Three main methods of weaving with nylon were explored. In the first method demonstrated in Figure 3, strands of nylon were drawn from the two-phase nylon pre-polymer solution either by hand or by the robotic arm. Variations in strand thickness were easily controlled and achieved by modifying the speed at which the strand was drawn with faster draw times resulting in thinner strands. Thicker and stronger fibers can be created by using wider containers for the nylon synthesis and by adding certain agents such as detergents and glycerol to modify surface tension; Hollow cavities in the strand can be created by changing the drawn sequence and occasionally reversing the draw direction. These cavities may potentially be filled with additional materials or glue in analogy to the drop of glue found on some spider silks.

In the second method seen in Figure 4 (left), the nylon prepolymer solution was placed on the table in front of the robotic arm and a weaving frame with pegs was attached to the arm. Nylon strands were wrapped onto the weaving frame by twisting and manipulation the robotic arm in six axis. In the third method (Figure 4 (right)), the frame was stationary while a shallow container of the nylon prepolymer solution was manipulated such that different hooks were submerged into the solution successively, resulting in multiple strands.

Creation of Nylon 6,6 skins

By using a method of turning and drawing, thin skin-like membranes can be created. A fixed frame constructed with MDF pegs was used and a shallow container of nylon prepolymer solution was dipped and rotated onto pair of adjacent peg, successively (Figure 5 (left)). Formulating the nylon prepolymer solution with 50% by volume of bubble solution resulted in a stronger and larger nylon skins when drawn using multiple or cylindrical hooks (Figure 5 (right)). Various amounts of water-based coloring agents and bubble solution may be further added to the aqueous solution to alter the optical and mechanical properties of the resulting nylon skin.

Conclusion & Future Explorations

Drawing inspiration from the spider silk system, CNSilk seeks to develop a material synthesis and fabrication approach for structures whose architectures, responses, and process of fabrication are informed not only by a static design but also by the properties of the fiber itself and its surrounding environment. At its core, CNSilk explores the concept of material synthesis as an integral part of the fabrication process, where tensile members are dynamically generated to adapt to current environmental factors. The intent of this approach is to allow the material system to function in a less intensive way than electronically driven methods, embedding the technology into the system rather than it functioning as a supplement. Continued development of this research could potentially be adapted to integrate material and density gradients to incorporate both structural skin and apertures through either a single or multiple materials.

References

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Figures

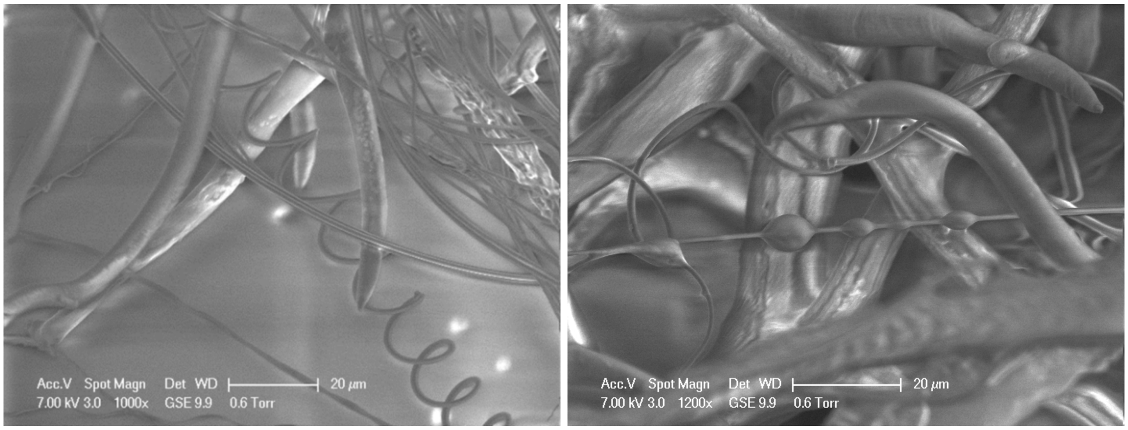

Figure 1
Environmental scanning electron micrographs of spider silk fibers illustrating the different structures present including spring-like motifs (left) and droplets of glue (right).

Figure 2
Image of the KUKA arm with a holder attachment containing a spool of yarn. The arm is inside a metal frame enclosure with protruding hooks serving as support for the yarn.

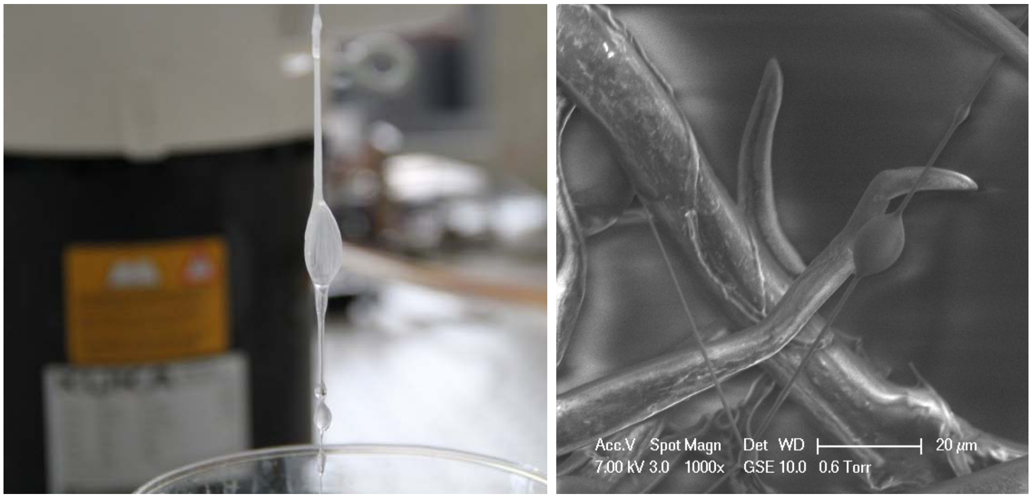

Figure 3
Nylon 6,6 being synthesized and drawn out of a 2-phase liquid system by the robotic arm (left) and an electron micrograph of spider silk containing micro-droplets of glue (right). Different thicknesses and bubbles may be created by varying the draw rate and technique.

Figure 4
Robotic Arm manipulating the weaving frame that the nylon is being wrapped around. The nylon prepolymer solution is resting on the table below the arm (left). Nylon threads attached to hooks on a steel frame formed by dipping the hooks into a nylon prepolymer solution.

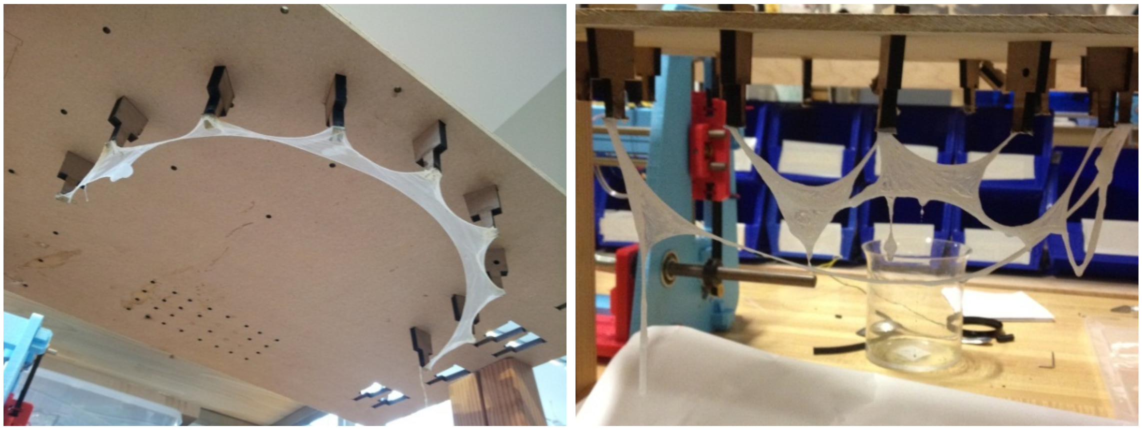

Figure 5
Images of nylon 6,6 membranes created by turning and dipping a shallow container of nylon prepolymer onto adjacent pegs (left) and by formulating the nylon prepolymer solution using 50% bubble solution (right).