3D Printed Textiles from Textile Code: Structural Form and Material Operations

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ABSTRACT
Translation of 3 traditional textile structures to digital code to make 3D printed textiles is discussed in this paper. The relationship of the behavior of that printed textile to the geometry and material of the textile unit is also examined. If architects, designers and scientists developing textile technologies for buildings, clothing or other objects can begin to understand and digitally construct different categories of textile structures, as well as understand how the behavior of that textile relates to its structure, then they can better understand how to design form active systems, or structures that are able to move when required.

KEYWORDS: 3D Printed Textiles, Textile Code, Textile Structure Classifications, Textile Structures

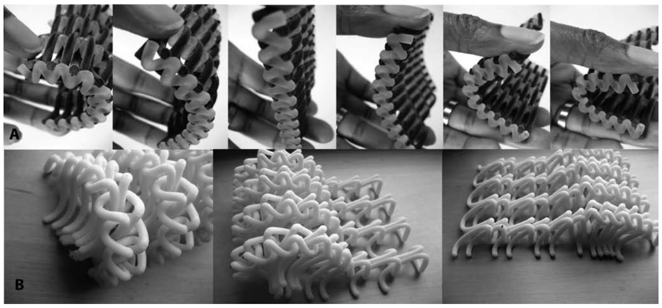

Figure 1. (A) 3D Printed Weave with Rubber Warp and Black ABS Plastic (B) 3D Knitted Print in ABS Plastic, compressed to open state.

Introduction

Much work has been done in the last 5 years on developing strategies of coding 3D textile models in popular 3D modeling software, however the problem is that the modeling of the same basic stitch is done in many ways, and principally for visual effect rather than for a specific behavior in the fabric.[Alquist and Menges] A second problem is that these methods of programming are never discussed in the larger context of all textile structures thereby missing possible strategies for designing many kinds of stitches with similar code methods. Information about code methods to construct a stitch is unlike the informal body knowledge of learning the geometry of a stitch where visual information is memorized in body knowledge of how to construct that stitch. A simple abstraction of some of the basic code methods can help designers interested in working with textile code to work more intuitively, with many different kinds of 3D programs to design textiles.

The discussion in this paper expands a traditional idea of textile craft through digital coding for 3D printed textiles. The author presents a basic coding classification system for three principle textile structures. The classification of the textile digital code is discussed in relationship to the textile structure classification system *and* in relationship to the coding used by textile designers for each type of textile. A method of modularizing textile digital code to make the code simpler and make use of 'plug and play' stitch algorithms so that many kinds of textiles may be quickly coded in a related manner is presented. The 3D printed textiles presented in the paper demonstrate specific parametric relationships between geometry and the behavior of the overall textile 3D print. Different parameters are developed to obtain different behaviors in the 3D printed textiles, such as elongation, compression, twist, bend etc. multi-material 3D printed textile examples are also discussed.

Three traditional textile geometries are discussed including a linked structure, a knitted structure, and lastly a woven structure. Each of these textile systems is discussed in terms of the components that make up a unit and the repeat of that unit to make up a larger piece of the textile. Each textile is placed in relationship to other textile geometry in a classification table and organized according to the behaviors that are possible within that basic geometry for each textile.

Related work

The works that are salient include those projects that relate the tradition of textile construction to code or parametric software to create a 3D printed textile structure. More specifically, focus is on work that looks at the material behavior in relationship to that structure rather than focusing on generating the form of the 3D print.

Palz and Thompsen expand the concept of traditional crafting of textiles by their use of digital modeling and digital 3D printing techniques. In this article Palz and Thompsen explicitly discuss the possible motions that a knit knot unit has as a 3D print. Palz further develops a concept of tunable materiality in 3D printing in his PhD research to understand material behavior in the printed object. In his fascinating publication *Generative Algorithms: Concepts and Experiments in Weaving*, Khabazi outlines loom weaving using Grasshopper a parametric 3D modeling software, but the focus is on geometric representation not behavior of that geometry. Other relevant examples of 3D printed objects that use variable material printing to achieve specific behaviors include Neri Oxman's Fabricology or *Wrist Splint* 2010 that tests variable property 3D printing to provide support or flexibility in different s areas in a printed splint.

Classification system for textiles as method for generating textile code

The classification system for textiles presented by Irene Emory in her book the *Primary Structures of Fabrics: An Illustrated Classification* outlines a way to understand the variety of textile structures, where structure is defined as the geometric relationship of the elements or yarns to each other. Figure 2A shows a chart based on Emory's classification of textile structures.

There are 3 overall categories of yarn relationships including *interworked* elements that include linked stitches, knitting and other knotted fabrics, *interlaced* elements include all the woven structures, where yarns or threads go over and under each other without knotting, and lastly *felted fibers* or non -woven fabrics which are dense mats of fibers. In this paper, 2 two types of primary structures are discussed, 2 in the interworked or knotted category, and one in the interlaced or woven category. These are shown outlined in red in Figure 2A. The first is a single link, the second a plain knit, and third a woven structure. Felted fibers will not be included within the discussion and presented in later work.

This traditional classification of textile structures is used to generate and classify textile code. Classification of textile structures by *code* is shown in Figure 2B. Here the two major categories, interworking, in this instance using one strand and interlacing, which requires two or more strands are modularized in the code to operate in a similar manner. Starting with the Single Link for example, the algorithm uses one strand, in this instance of interworked elements or a minimum of two strands in the case of the interlaced category or a plain weave. These algorithms are plugged into a module that determines the area covered by the stitch, the spacing of the units in the xy plane in that area and, offset of the yarn(s) in the z direction. This module makes the stitch algorithm the primary mode of 3D textile model classification aligning it with the Emory textile structure classification system so that it can useful to textile

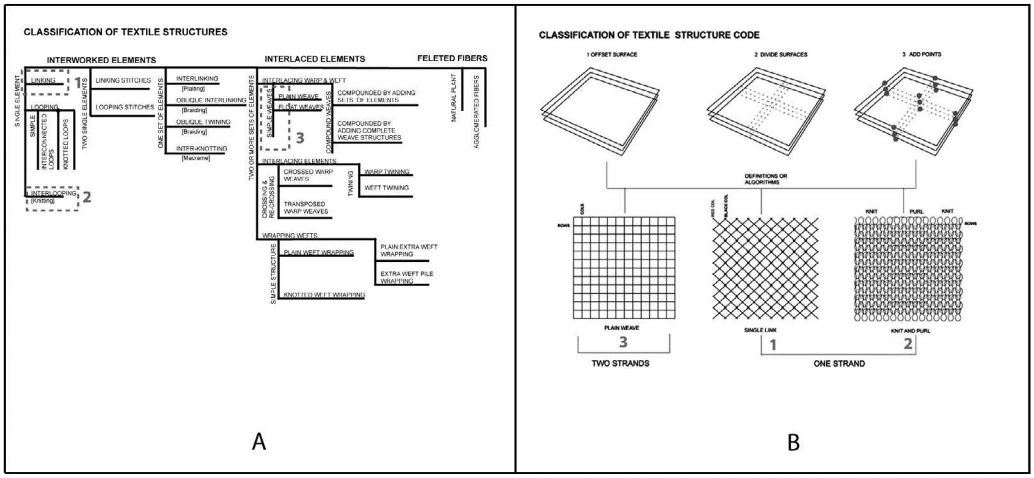

Figure 2 (A) Textile classification by relationships of yarn geometry (B) Textile classification by code structure

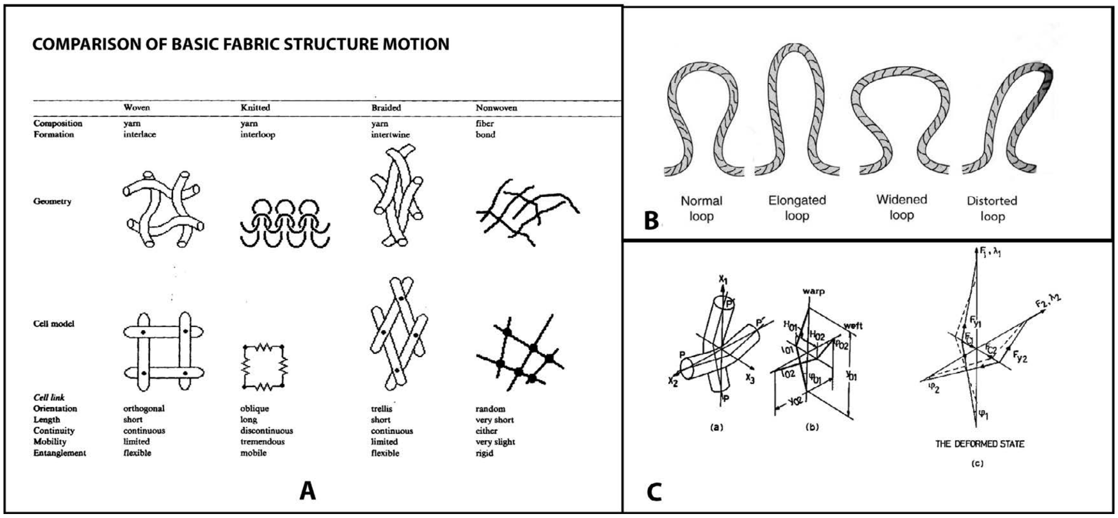

Figure 3 (A) Degrees of Motion for Textile Geometries from Scardino (B) Elastic Motion of Knit Loop from Kadolph (C) Deformed Weave from Kawabata.

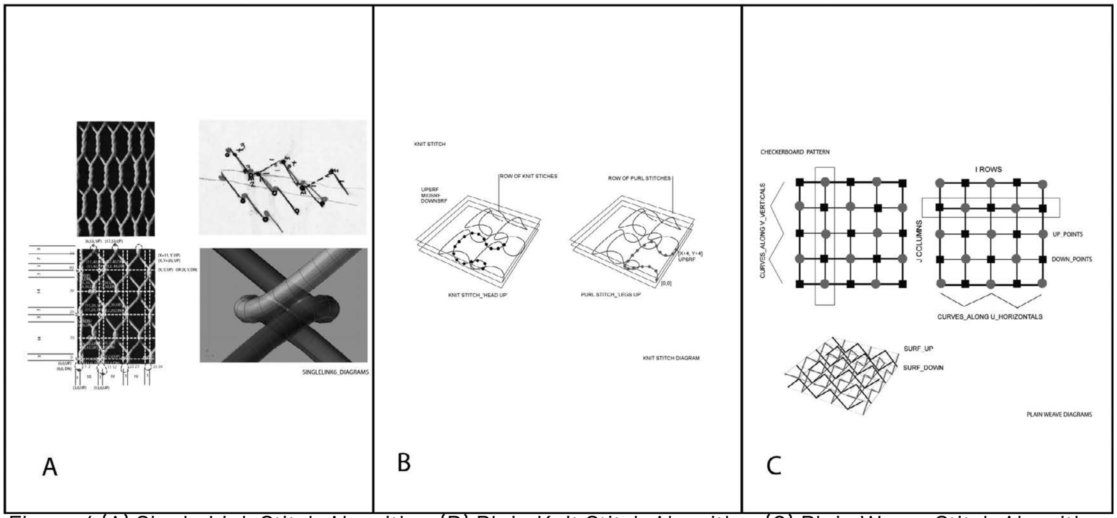

Figure 4 (A) Single Link Stitch Algorithm (B) Plain Knit Stitch Algorithm (C) Plain Weave Stitch Algorithm

designer who wish to make 3D printed textiles and the architect who wants to relate structure to behavior, *and* many kinds of textiles may now be designed in code using a base module.

Textile designers have well established methods using visual and embodied computational techniques to design different stitches. These include the checkerboard patterns specifying the over under sequences that weavers use to develop their fabrics and the binding patterns that represent knitting machine needles in section that knitters use to construct their patterns. The weaver's checkerboard is quite close to how the code described in this paper operates. Woven materials can have a great deal of stiffness making this textile structure more closely aligned with traditional architectural building processes. However, the knitter's binding pattern is must be treated in another way for 3D printing because the pattern is based on the wrapping of flexible yarn around a needle. The knitter's binding pattern must be reinterpreted in the code to create the knit in a 3D print. [Davis]

Geometry, algorithm, behavior

In each textile structure the geometry and disposition of the yarns to each other greatly determines the behavior of that fabric. An important issue that architects and designers working with textiles begin to learn through experience is relating how geometry of an overall system of units affects the behavior of something that can move. Figure 3A, shows a diagram that relates geometric structure to degrees of motion in a 2D plane. The point here is not to show all possible motions of the basic textile structures in this paper, rather the point is to show how preliminary diagrams can help the designer intuitively understand what can happen in a moving fabric structure.

The Single Link Stitch algorithm is one of the most ancient of structures and is a single yarn that is wrapped on itself to create a net like structure. The fabric itself can elongate and expand in along the long axis of the fabric as well as the short axis, but because it is a link structure the fabric can elongate in more than just these two directions, it can be pulled in many directions. In our 3D print of the Single Link the modular offset has been made large, thus making very large linear loops. This permits each link strand to rotate around each other along their long axis, if the ends are left open. Unlike the actual fabric, the 3D structure cannot move if the ends of the strands are connected to each other because they are linear. These large, linear loops also make it possible to compress and expand the textile along the short axis of the strands. Figure 4A shows the process of generating the Single Link Stitch algorithm.

The Plain Knit Stitch algorithm drives a line through a sequence of points in order. The line is then piped with a separate pipe algorithm written for loop stitches. The knit stitch is a looped stitch that can hang together, even when a cut is required at the edges of the printed fabric to allow it to move. More studies need to be done on making adequate looped closed end conditions for the 3D printed link stitches and knits that will allow them to move. A loop or closed ring is optimal for 3D printed fabrics because they hang together without falling apart. Movement is by compression and pulling apart of the lines of loops, as well as rotation around the long axis of the stitch line. In the 3D knit prints shown in this paper, the modular offset is again set a bit larger so that the legs of the loops allow for play in the fabric. See Figure 4B.

The Plain Weave stitch algorithm is an algorithm that drives two sets of lines between an upper and lower plane from point to point in order. The plain weave 3D print has a different set of requirements to happen. First of all the weave yarn must be thick enough to at the least have a slight overlap into the other yarn diameters so that it does not fall apart. The larger the offset, the larger the yarn diameter must be. This requirement prevents it from moving as a print. It cannot rotate, bend or flex. More work can be done here to understand if the basic weave structure can move without this overlap, without falling apart. In this instance the requirement of movement was developed by introducing another material into the 3D print that itself was elastic. See Figure 4C.

Piping or gauging the yarn thickness was critical in these 3D prints. In fact piping is not straight forward for each algorithm, specifically those that called for very long offsets in the base module such as the offset that produced the spikes as seen in the Woven Ball (Figure 5C) or 3D digital models with very thick yarn made for uneven sections in that yarn. These models could not be printed. This required resetting the textile offset parameters to suit the given basic yarn formula, or making a more robust yarn algorithm so that all sections of the yarn remained circular at all times. This was called 'getting gauge' on the textile prints.

Material

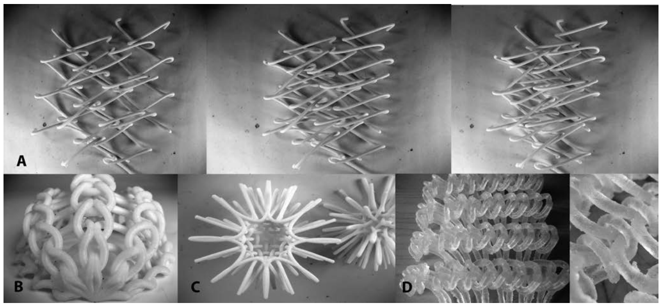

Figure 5 (A) Single Link open state to compressed state, ABS Plastic (B) Plain Knit Half Sphere, ABS Plastic (C) Plain Weave Half Sphere, ABS Plastic (D) Plain Knit, Clear Rubber Knit.

As seen in the Plain Weave Stitch 3D models, there is no movement in the fabric without the introduction of other materials to the standard ABS plastic print. Warps or wefts of rubber or flexible plastics provide flexure in the textile weave print as seen in Figure 1A. Rubbers and flexible plastics also give knit and linked stitches another dimension for mobility through elongation and stretch in the fabric seen in Figure 5D. This material has a large impact on a 3D knit in that it can become so elastic as to become unstable. Also the rubber used in current commercially available printing machines is not very stable. Over time the knitted patterns printed with this have become much more elastic. Additional work can be done to understand how the variability of the materials in the prints can work to create useful materials. More work can be done to look at not only the current paradigm of materials that printed are side by side, but also combined in the printing nozzle or printing bed at a chemical level to develop rich behavior for 3D printed textiles. Figure 5 shows a variety of ABS plastic and rubber based 3D printed textile models. Figure 5A and 5D are textile prints that move, Figure 5B and C do not move.

3D Printed Fabrics

There are thousands of woven and knit patterns that people have invented and re-invented over the ages, since the beginning of textile craft. Some of these can be reinterpreted in code for use in new textile applications; however the final fabric behavior will be quite different from the inspiration textile for now. Many new textile patterns have been invented such as Fizel and Huang's N12 Nylon Bikini that uses circular discs threaded together by a printed strand of N12 nylon. This fabric adjusts the size of the disc to fit the curves of the body, with smaller discs allowing for higher curvature on the body. In architecture and design, 3D printing methods hold great promise in terms of providing a way for architects and designers to design the behavior of their own materials that in turn can transform how building is done.

Contributions

This paper provides a larger framework for understanding 3D printed textiles by using textile structure classification as a way to understand a context for structuring textile code for many types of 3D modeling software. In addition to referencing historical textile structures and expanding the discipline of textile design and textile craft into digital 3D printing the paper demonstrates a method to work with modularized code for many kinds of textiles. The paper demonstrates through the process of writing algorithms, and testing through several 3D textile prints a method designers can use to consider the relationship between geometry, behavior and material in 3D printed textiles.

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