Weaving Objects: Spatial Design and Functionality of 3D-Woven Textiles

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ABSTRACT

3D weaving is an industrial process for creating volumetric material through organized multiaxis interlacing of yarns. The overall complexity and rarity of 3D weaving have limited its market to aerospace and military applications. Current textile design software does not address the ease of iterating through physical trialing so necessary for designers to access this medium. This paper describes the development of a series of volumetric textile samples culminating in the creation of a fully formed shoe and the collaboration with computer scientists to develop a visualization tool that addresses the consumer accessory design opportunities for this medium.

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While the potential for 3D-woven fabric is widely recognized, its deployment has been limited to applications such as ultrastrong, lightweight machine parts and composite forms, which largely derive their three-dimensional forms through the placement of thick woven fabric into molds [1,2]. The addition of a third dimension—40+ layers of stacked yarns—suggests a far richer sequencing by which layers can connect and molds can be inserted to generate cavities, channels, pockets, flaps and hinges. Breaking open the spatial realm of 3D-woven fabric and making the medium more accessible for functional consumer-based product design requires both a setup that is aligned with current textile design methodology and a tool that allows ease of iteration. Our extensive physical trialing of 3D-woven architectures has unveiled a multitude of behavioral tendencies that are used as the functional vocabulary for designing in this realm and by which we can effectively collaborate with computer scientists to develop a new tool for visualizing the complexity of the inner workings of a 3D-woven textile sample. We then used these tendencies, together with this tool, to create a fully formed 3D-woven shoe.

Toward a Design Methodology for 3D-Woven Textiles

Typically, the Jacquard mechanism is utilized to translate graphic files into two-dimensional fabrics with relatively few layers. Our aim is to adapt this process for multilayer volumes by conceptualizing 3D-woven structures as compilations of small architectural blocks. To do this, we utilize a specialized setup for the Jacquard loom, explore existing practices and develop a design methodology to harness this mechanism on all axes of the woven object (Fig. 1).

The Language of Jacquard

The Jacquard loom is an industrial tool that united the hand, the machine and one of the earliest computer systems for translating an image into a simple binary language that encodes interlacings of warp and weft yarn. The technology has greatly evolved since its invention over two centuries ago, becoming faster and more precise through the implementation of different computer-aided design (CAD) systems for translating digital artwork files into binary images. Yet the binary language itself is an archaic way of representing the interaction and behavior of yarns. A standard black-and-white file (the "card image") can convey which yarns are on the face and which are not, but reveals little about the behavior of yarn movement when extrapolated to compound weaves. This problem is most pronounced in 3D weaving, a form of extreme compound weaving, as yarns move horizontally and vertically, as well as on a third axis throughout the volume of the textile.

doi: 10.1162/LEON_a_01780
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Fig. 1. A 3D-woven shoe: woven in one form on an industrial Jacquard loom. (© VTRG 2019. Photo: Emily Holtzman.)

3D Weaving Techniques and Practices

In traditional 2D weaving, warp ends travel in the vertical direction and are usually assembled under tension on a beam, or large roll, while the weft yarns travel horizontally and are passed above and below the warp ends to create interlacings and woven patterns. 3D weaving utilizes these basic premises but with some significant variations. First, 3D-weaving techniques enable multiple layers of fabric to be joined together, sometimes linking layer to direct layer and sometimes running individual warp ends in a cascading motion throughout the fabric as "Z-tows" in a process called angle interlock (Fig. 2). This movement adds to the vertical warp action and horizontal weft action to create a third axis within the cloth. Second, the number of layers and the size of the materials significantly impact the duration of weaving. Third, 3D weaving utilizes a creel for warping, which comprises an array of yarns that are placed individually on a rack behind the loom. The creel allows each warp end to maintain tension, using as

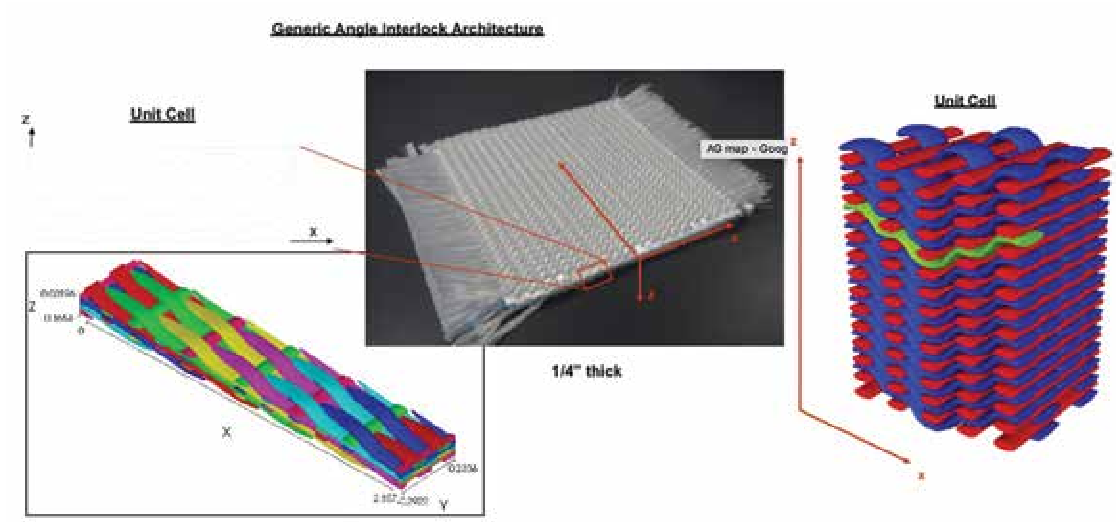

Fig. 2. 3D-weaving architecture: the interlocking movement of warp ends through each layer of a 3D-woven fabric. (Images courtesy of T.E.A.M., Inc., Woonsocket, RI)

Fig. 3. 3D-weaving loom and castout: industrial Jacquard loom for 3D weaving with creel and detail of harness. (Courtesy of T.E.A.M., Inc., Woonsocket, RI. Photo: Emily Holtzman.)

much or as little of each warp as necessary throughout the fabric. The variable warp lengths combine with the Jacquard mechanism to allow customizable architectures in the fabric [3].

Many Jacquard-woven 3D fabrics are simple and take the form of rectangular billets molded into shape for the composites industry [4,5,6]. A 3D-weaving setup requires a castout designed for depth and density rather than width, a key difference from more traditional decorative or greige woven goods. This depth-prioritizing setup is essential for enabling the warp yarns to stack on top of rather than next to one another [7] (Fig. 3). Equally vital is the weft insertion sequence and mapping the shuttle path throughout the fabric. Given that most 3D-weaving setups incorporate a single shuttle, the same weft yarn must be programmed to pass entirely or partially across the fabric and to repeat actions in different sections of the fabric to build up necessary depth and material bulk.

Computational Tools

Current CAD tools for 3D weaving provide little information about yarn behavior within fabric. 3D fabric designers commonly work from sketched diagrams to transpose complex card images manually. We begin the process using Pointcarre, an industry standard textile CAD platform that maps weave structures to color pools in a graphic image [8]. Pointcarre allows for dexterity in traditional fabric design, but is insufficient for 3D-weave design, failing to fully engage the complexity of layers within a 3D setup. Without spatial organization of 3D-weave structures, it is common for fabrics designed in Pointcarre to contain unnoticed errors. For more precise work, we require a binary tool in the form of a Microsoft Excel sheet containing an array of hooks for distributing the design pattern and shuttle path. As the graphic file usually originates in Photoshop, current practice requires the use of a combination of Photoshop, Pointcarre and Excel to attain a working 3D-weaving file (Fig. 4).

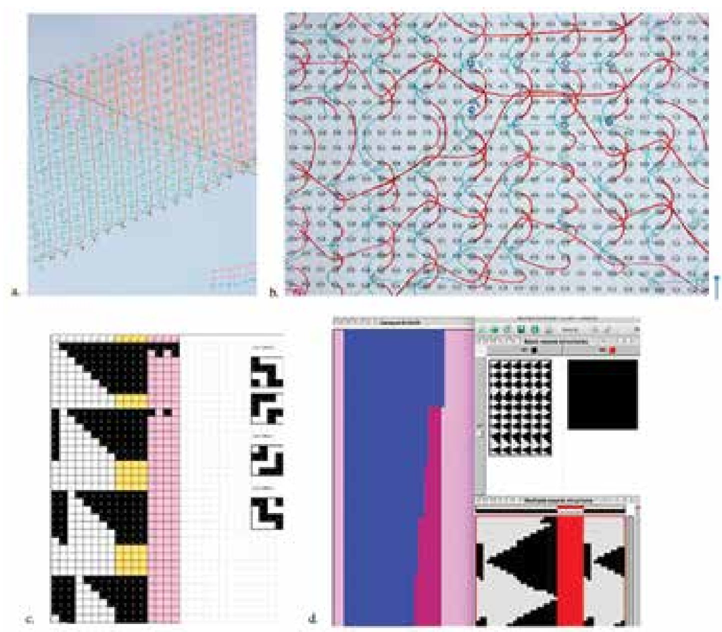

Fig. 4. Current design methodology: a. sketch of yarn paths in 3D file; b. sketched shuttle pathways; c. file in Excel; d. Pointcarre assembly of Photoshop structures. (© VTRG 2019)

Using this patchwork of programs, while ultimately effective, is tedious and error-prone. The few software platforms that exist for visualization of 3D-weave structures such as Scotweave only permit constant weaving of the same architectural billets and do not support variations in the topography of the fabric or weave edge compatibility and shaping through controlled shuttle passage [9,10]. Pointcarre was not developed with the goal of creating 3D wovens and fails to address variations in depth or shuttle movement, since the program simply tiles out the card image to be repeated in all areas of a color. This enables building catalogs of compatible weaves and populating a graphic image with structures, but gives little control over the actual movement of the yarn between the color pools or the attachment of discrete layers. While it is possible to craft a card image for these complicated design issues using current design tools, it remains difficult both to visualize and edit designs developed in this way (Fig. 5).

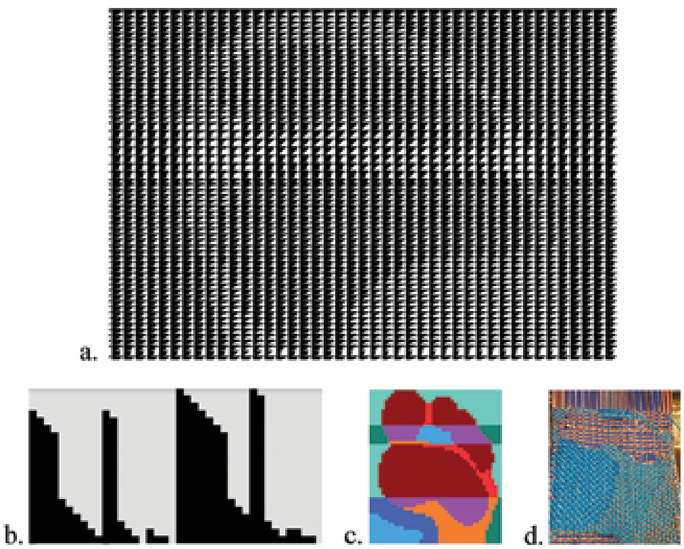

Fig. 5. Building depth in Pointcarre: a. card image for the toe, ball and arch of insole; b. use of supplementary wefts for depth in 2D Pointcarre file; c. graphic file for building layers; d. woven sample with thick and thin areas. (© VTRG 2018)

A New Approach

Partnering with textile manufacturer T.E.A.M., Inc., we have accessed industrial weaving equipment to develop a range of samples exploring material and behavioral properties of 3D-woven textiles. Through ongoing collaboration with computer scientists at Cornell and Stanford Universities, we have aided in the development of a software platform that allows for the design of weave "blocks" that aggregate to complex 3D fabrics. The samples, together with the card images and the experiences gained from the production process, have lent critical insight to the platform development. Each iteration of the platform in turn has further streamlined an otherwise cumbersome workflow and enabled more trialing.

To develop this new tool, we began a dialogue with the computer scientists about the challenges and inefficiencies of current platforms. For further reading, please see Irawan, Kaldor, Leaf, Miguel et al. [11,12,13,14]. Traditional woven design workflows do not address the specific problems inherent to 3D-woven design, such as shuttle passageway, weft sequencing or varying depths of pick columns. To efficiently design 3D-woven goods, a new design tool needed to combine the precision of 3D-weave hand sketching with the ease of textile CAD interfaces. This tool would allow easy programming in fabric cross sections that could join together and be viewed spatially. Customization of weave blocks would allow the designer to articulate junctures and shuttle passage within the overall fabric. Upon design completion, an accurate card image would be automatically generated to drive the loom. The new tool that has emerged, Weavecraft, gives designers a way to visualize, collect and design weave structures as spatial architectures and provides a path for creating complex 3D-woven objects.

The Project: A 3D-Woven Shoe

Given the specialized nature of 3D weaving as a way of creating volumes with woven fabric and its underutilized potential for complex object formation, we seek to demonstrate the capacity of the medium by creating a technically sophisticated shape in the form of a 3D-woven shoe. We chose to create a shoe as a grand challenge to test our ability to understand the medium and to engage the dominant design object in this domain, the Nike Flyknit sneaker, which has profoundly changed the market since release in 2012. We ask: Can an entire complex volume be produced through weaving rather than knitting or even 3D printing? A shoe is a functional object and an ideal vehicle for addressing many of the design issues emerging from 3D weaving, such as varying density, layer linkages and shaping of distinct functional zones.

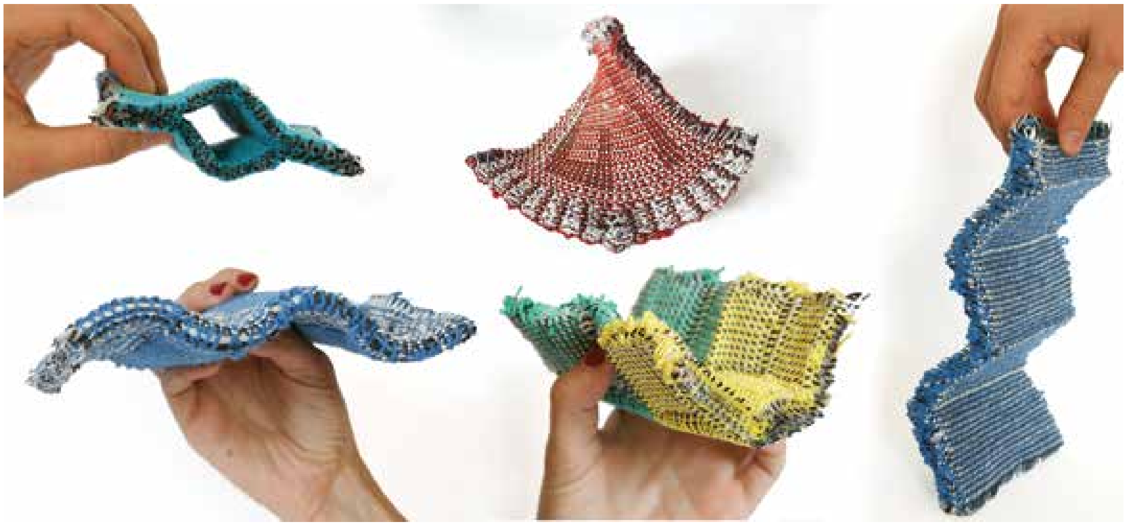

Fig. 6. A library of tendencies: samples depicting physical behavior of 3D-woven fabrics: (clockwise) layered graphics with hinge effect; semirigid creases; stuffed creases; directional arches; crenellated pocket. (© VTRG 2018. Photos: Emily Holtzman.)

Library of Tendencies

We began by creating samples of experimental 3D-woven architectures. As the samples evolved, a vocabulary of different behavioral tendencies emerged, which in turn drove the final form of the woven shoe. A *tendency* can be defined as a predictable behavior of a fabric caused by a combination of weave structure, 2D graphics and materials. In creating these samples we utilized structures and graphic files that would result in the physical transformation of the fabric, but would not be legibly represented by the traditional 2D binary draft. We created a library of these tendencies to be deployed at different zones throughout test fabrics to aid in the creation of volumes (Fig. 6).

Sample TL013 (Fig. 7a) displays a strong physical tendency, with wefts that build up to meet at an apex, followed by a downward trajectory to a minimum, making densely woven crenellated fabric with a thinner surface layer floating on top and bottom. The difference between the upward and downward stacks is a simple inversion of structure, but the physical impact is pronounced and embodies a tendency for a directional "zigzag." The team at Cornell simulated TL013 in Weavecraft and verified much of its behavior using a CT-scanned cross section of the fabric (Fig. 7).

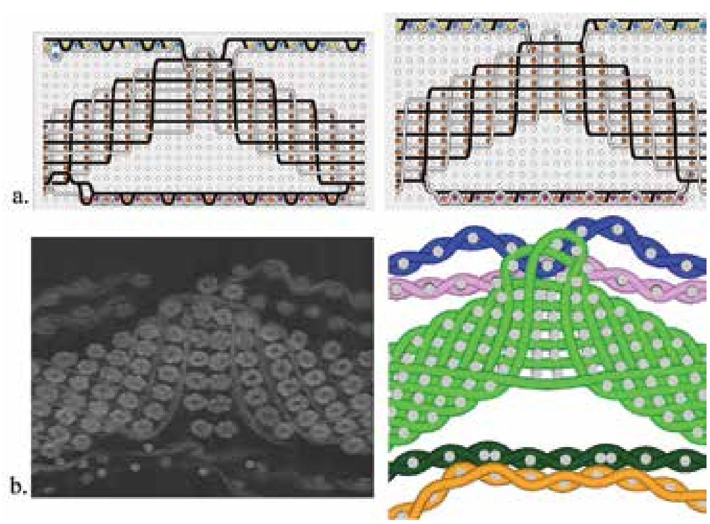

Fig. 7. 3D-woven file comparison: a. TL013 original file compared to Weavecraft file with changes apparent; b. comparison of CT-scan of TL013 and relaxed simulated version. (© VTRG 2018. CT-scan and simulation images courtesy of Jonathan Leaf, Doug James, Rundong Wu and Steve Marschner.)

Further samples demonstrate the addition of jacquard graphics on various layers of the fabric and the presence of volumes or pockets within the fabric, as well as how graphic areas could be developed as topographies with varying amounts of material contributing to shifts in the overall thickness of the design.

The Shoe

Our 3D-woven composite shoe derives its form, materiality and structural integrity from the textile itself. By approaching the design of a shoe as a fully formed woven object, it is possible to streamline many of the secondary processes usually

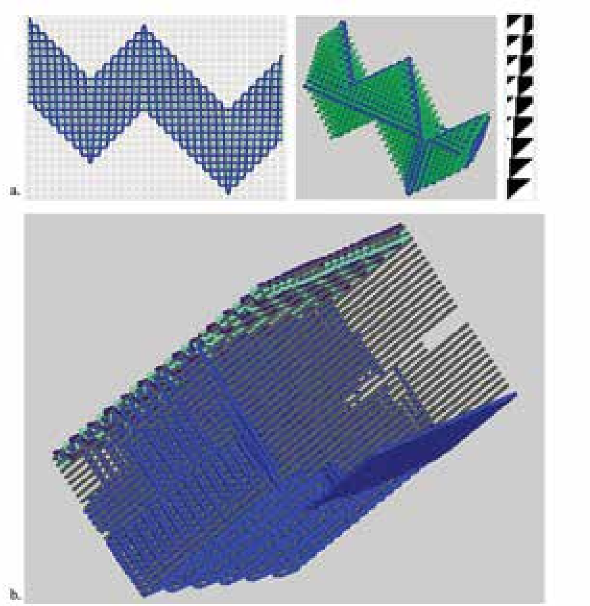

Fig. 8. Weavecraft design for the 3D shoe: a. SliceEditor, 3D Viewer and card image output file; b. complete 3D file for shoe (sample portion). (© VTRG 2018)

associated with shoe fabrication. Seaming, gluing and molding can be translated into woven manipulations, creating a shoe preform that requires only trimming and molding off-loom to create a finished, stable product.

In organizing the warp, we divided the shoe into three zones: the sole, the insole and the upper. These zones draw from our library of tendencies and were executed in specific materials to enhance their physical behavior. In the shoe sole, we executed a variation of TL007 in a PVC-coated polyester yarn to create a flexible tread. The insole, executed in 5/2 cotton, provided areas of cushion and support. The fine cotton upper provided the means to create a deflected weft graphic fabric. These three major zones, defined by their material properties, can be edited separately using Weavecraft.

As samples were developed and woven, we were able to cut, sew and alter the existing shapes to envision a new weaveable design feature (Fig. 8) that could be incorporated into the structure of the next woven prototype. By making proportional changes in our jacquard graphic, new sizes and dimensions could be woven. We have the further ability to customize the materiality, size and flexibility of the shoe preform by using different weft materials while weaving, or by swapping out warp ends for visual or structural effects.

Creative Process

The design of the shoe begins with the composition of the warp, which is broken into three distinct zones for the sole, the inner and the upper. Within these areas, yarns of different sizes and materials have been planted in stripes to aesthetically emphasize the center of the shoe and imply light and hue transition over an abstract cylinder form. Different size wefts can be inserted strategically to further bulk up the heel of the shoe or encourage flexibility at the toe bend. The visual design of this shoe is a result of finding woven solutions to traditional shoe components while taking advantage of the flexibility and freedom of jacquard weaving.

When designing, each sample informs the development of the next. We deploy our understanding of structure and the tendencies that have been sampled previously to create dimensional effects such as the linked crenellations of the sole and the foot-shaping topography of the inner, while utilizing the Jacquard mechanism as a drawing tool for graphic marks.

Evaluating Weavecraft

The Weavecraft software consists of three easy-to-use windows that together provide the information needed to effectively design 3D weaves. The first window, the SliceEditor, allows the designer to set the number of wefts and warps that are active in a particular zone and draws the physical pathway of each warp yarn around the wefts. The slice can be replicated as much as needed for a particular design zone and loaded in the second window, the 3D Viewer, which provides a multiaxis view of the interlacing yarns and can be rotated spatially. Slices of different heights can be added together, and slices can be stacked on top of other slices to enable the unit-by-unit construction of a 3D form. Finally, Weavecraft generates the standard 2D binary file necessary to run the Jacquard mechanism, which only has to be converted to the proprietary JC file language to run the loom (Fig. 8).

Fig. 9. Iterative process: various shoe versions, following removal from loom; following postproduction finishing; separation of tongue and heel; insertion of laces. (© VTRG 2019. Photo: Emily Holtzman.)

Weavecraft's easy editing of slices and assembly of blocks made creating files for the shoe logical and editable. Given the amount of time it takes to set up and create a 3D-woven sample, Weavecraft is a tool that exponentially increases efficiency and opens the door to a rich iterative design process.

Conclusion

Accessing 3D weaving as a medium for designers necessitates new methodologies and tools. To produce complex 3D wovens requires an upgrade in the Jacquard process that goes beyond laborious binary encoding to an integrated computational environment in which the designer can effectively sculpt soft woven forms. The parallels to other 3D fabrication technologies are obvious, and design in this medium is relevant to numerous industries such as soft goods, accessories, fashion, technology and medical accessories. For our design research team, the grand challenge of developing a 3D-woven shoe enabled us to explore a range of factors including materiality, functionality, weave architecture, postproduction finishing and adaptation of existing manufacturing platforms and processes (Figs 9,10). Our collaboration with computer scientists resulted in the creation of a new tool for accessing the medium. This tool helps us approach woven textile design in a new way, with the expectation that better modeling can provide more information about the behavior of complex fabrics and aid in the composition of multidimensional forms, a shoe being but one example.

Fig. 10. A 3D-woven shoe: final shoe v.2 (© VTRG 2019. Photo: Emily Holtzman.)

Acknowledgments

We thank T.E.A.M., Inc. for the generous donation of time, materials and equipment, and Prof. Doug L. James and Jonathan Leaf of Stanford University for rendering and visualization discussions. Thanks to Alison Huff for varied assistance. Thanks to RISD Virtual Textile Research Group (VTRG, www.vtrg .squarespace.com) 2016–2019: Anjuli Bernstein, Gabrielle Ferreira, Claire Harvey, Emily Holtzman, Carolina Jimenez, David Kessler, Sam Lavoie, Anastasia Onegina and Emily Robertson.

This work is supported in part by National Science Foundation (NSF) IIS-1513954, and a gift from Under Armour.

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