Generative Design in Textiles: Overcoming Problems of Production

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Abstract

In this paper we discuss some recent work towards producing high-quality woven textiles that incorporate generative design elements. In particular, we describe our efforts to circumvent several problems of production that arise when woven textile designs are generated algorithmically. These problems can be summarily described as: (1) most commonly available floor looms are not capable of weaving generative designs without extensive, time-consuming, manual intervention by the artist and (2) generative textile designs must be developed in accordance with basic principles of textile production if the final piece is desired to be a sturdy and resilient textile.

We describe efforts to address the first problem of production by constructing our own, inexpensive yet full-sized, computer-controlled Jacquard loom for which we have written our own software. Additionally, we discuss an approach that utilizes “shaft switching” techniques that allow traditional floor looms to produce generative designs without an excessive amount of manual intervention. We also discuss some ideas for generative algorithms that result in well-made, sturdily woven objects.

Introduction

Traditionally woven textiles can be abstracted as binary matrices. In each row, a zero or a one indicates whether a weft thread (running left to right) lies above or below the corresponding warp thread (which runs from top to bottom). In fact, the traditional “weaving plan” is essentially a matrix of black and white gridded squares.

Viewed in this way, woven textiles present an interesting opportunity for the creation of art/craft that incorporates generative design since the weaving-plan-as-matrix can be algorithmically generated using cellular automata, stochastic processes, reaction-diffusion equations, or any number of other mathematical or computational schemes that generate or modify two dimensional binary arrays.

However, two significant difficulties arise when an artist attempts to move from an abstract, generative textile design to a physically woven object. Both difficulties are problems of production. The first difficulty is that most traditional floor looms are not capable of weaving generative designs without extensive, time-consuming, manual intervention by the artist. This defeats the primary purpose of the loom as a machine to automate many of the processes involved in the manufacture of woven textiles. Certainly, there do exist mechanistically advanced looms, known as Jacquard looms, which are capable of producing any possible weaving pattern, but these looms are expensive, are typically controlled by proprietary software, and are not very accessible to the average weaver.

A second, more fundamental, problem exists, however, in that a sturdy and well made woven object can only be produced if the underlying design conforms to basic principles of textile production. That is to say, a weaving design that looks good on the screen will, nevertheless, be a failure if it results in loose threads, or long stretches in which the weft is disconnected from the warp. Hence, a good generative textile design must always defer to the physical realities of the medium.

A number of other artists and researchers have explored generative design for textile production. For example, a team from the Carnegie Mellon Textiles Lab have explored using computer vision and collaborative editing [1], as well as gamification and real-time feedback [2], to produce generatively designed textiles. Researchers at the ATLAS Institute at UC Boulder have explored how materials, data, and humans collaborate to produce “personal data narratives” using woven artifacts crafted from personal data [3]. Miles Visman discusses the “space between randomness and order” that emerges when random processes are incorporated into proscribed weaving patterns [4].

From an early 20th century perspective, the Bauhaus School in Germany (1919-1933) was at the leading edge of textile design, asserting a modern perspective on combining fine art, craft, and commercially viable production. Two seminal weavers working at the Bauhaus Dessau Weaving Workshop, Gunta Stolzl and Anni Albers, incorporated the generative qualities of the newly acquired Jacquard looms into their textile designs (Figures 1 and 2). The Jacquard looms offered a means to actualize their weaving drafts and mock-ups into a degree of exactitude and complexity that previous hand looms could not achieve.

Figure 1: *Design for Jacquard Weaving, Gouache, Anni Albers.*

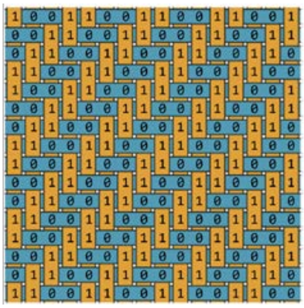
Figure 2: *(A) 5 Choirs, Jacquard weaving, Gunta Stolzl.*

Textiles as Matrices

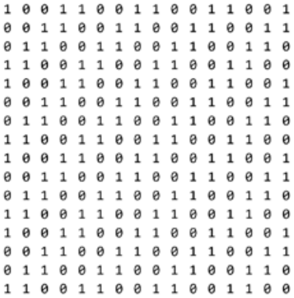
Traditionally woven textiles consist of two sets of interwoven threads oriented orthogonally to each other. Vertically oriented threads are referred to as the warp, whereas horizontally oriented threads are referred to as the weft. These two kinds of threads often have different properties (color, material, thickness, etc.) in so-called weft-face textiles, which are those in which the warp threads are not visible in the final piece. Rugs, carpets, and tapestries are often woven in a weft-faced manner where all the visible design elements are provided by the weft and the warp serves only to provide structure to the weaving. In any case, all the discussion in this paper applies equally to both weft-faced textiles as well as so-called balanced weavings in which both the warp and weft are visible in the final piece.

Shown in Figure 3A is a depiction of a woven textile. The structure of the piece is determined solely by the particular manner in which the weft (blue) is woven into the warp (orange). In this example, each weft thread alternately passes over two warp threads, then under the next two, and so on and the particular manner in which this is done is staggered. (This particular pattern is called a 2-2 twill.)

(A)



(B)



```
1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1
0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1
0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1
0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1
0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
```

(C)

Figure 3: *Weaving plan as a binary matrix.*

At each location where a weft thread crosses a warp thread we can record either a 0 (if the weft passes over the warp) or a 1 (if the weft passes under the warp) (Figure 3B). After discarding the weaving itself we are left with a binary matrix (Figure 3C) that records all the structural information of the weaving. In this manner, any textile has a corresponding binary matrix and the textile itself can be completely reproduced directly from the information in the matrix (provided we neglect superficial aspects like thread color, for instance). Hence, to generate a textile, we need only generate a binary matrix.

Generative Textile Design

There are many mathematical/computational ways of generating binary matrices. Probably the most well known are cellular automata which are systems that use simple rules to generate complex patterns. For example, John Conway's "Game of Life" [5] produces a time series of binary matrices in which the state (0 or 1) of any particular entry at time `t+1` is determined – according to a simple function – by the states of its 8 nearest neighbors at time `t`. This particular cellular automata is famous for resulting in complex patterns from random starting seeds. However, nearly all such patterns are unsuitable as a basis for a woven textile since they would invariably result in a very poorly made final product.

More suitable patterns can be produced using other cellular automata, however. For example, cellular automata that have been used to simulate various patterns found in that natural world (e.g., lizard skin [6, 7], snail shells [8]) can also be made to serve as the basis for textile designs. In Figure 4 we show a weaving plan based on a cellular automata that has been used to reproduce patterns found in the shells of cone snails. The algorithm is simple and uses the values in one row to determine the values in the next row: the entry `a(i+1,j)` in the (i+1)st row and jth column is determined by the sum `a(i,j-1) + a(i,j+1)` of the entries in the previous row that are immediately to the left and right where the sum is taken modulo two (that is to say, 1+1=0). This method of generating a binary matrix is closely related to Pascal's triangle. Nevertheless, while this design is somewhat suitable for a weaving plan, it would need to be modified to avoid long stretches in which the weft is not interwoven with the warp.

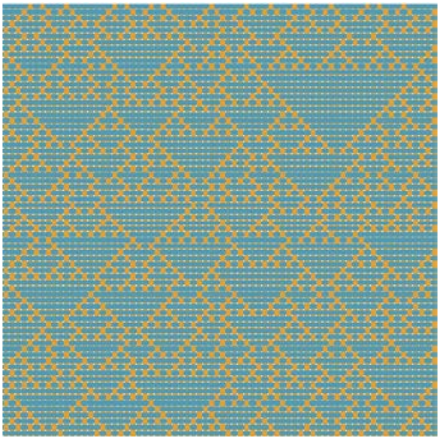


***Figure 4:** A weaving plan based on a simple cellular automata with a random seed.*

Rather than designing weaving plans from scratch using numerical algorithms, a different approach would be to start with a traditional weaving design, expressed as a cellular automata, and modify it in a generative way. We describe one example of such a design below.

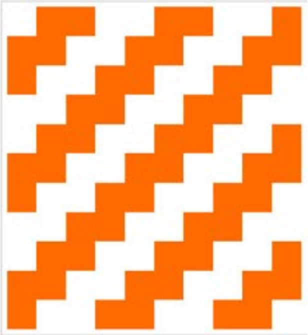
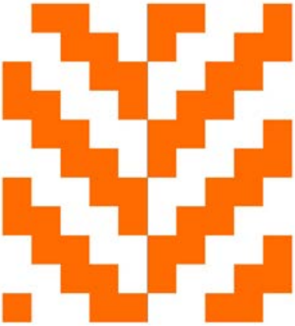


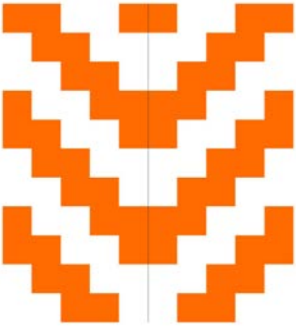
***Figure 5:** A standard 2-2 (left) twill pattern.*

A weaving plan for 2-2 twill can be described as a binary matrix with entries `a(i,j)` in which the first row is defined as 001100110011... and the entry `a(i+1,j)` in row i+1 is determined by the entry `a(i,j+1)` immediately above and to its right. See Figure 5. Of course, there is an analogous definition for a 2-2 twill that moves to the right instead of the left. In this case we would define the entry `a(i+1,j)` to be equal to the entry `a(i,j-1)` immediately above and to its left.

Given this simple algorithm for a standard twill, one could then ask what would happen if this weaving pattern were disrupted in simple, yet random ways. For example, after a certain number of rows, a column could be chosen at random and the direction of the twill (left or right) could be changed on one side of the column. For example, suppose a 2-2 twill moves to the left. We choose a random column and decide that to the left side of this column the twill direction will reverse and move to the right. We now have a twill design in which there is a convergence about the selected column and this convergent pattern will depend on which particular column was randomly chosen. See Figure 6.



(A)



(B)

Figure 6: *Two converging 2-2 twill patterns.*

On the other hand, rather than have the twill patterns converge about a column, we could choose to have them diverge as in Figure 7. Immediately, we see a problem, however, in that with a diverging twill we can obtain a weaving pattern in which there is a large area in which the weft is disconnected from the warp. Since this would yield a poor quality weaving, we must correct for this possibility.

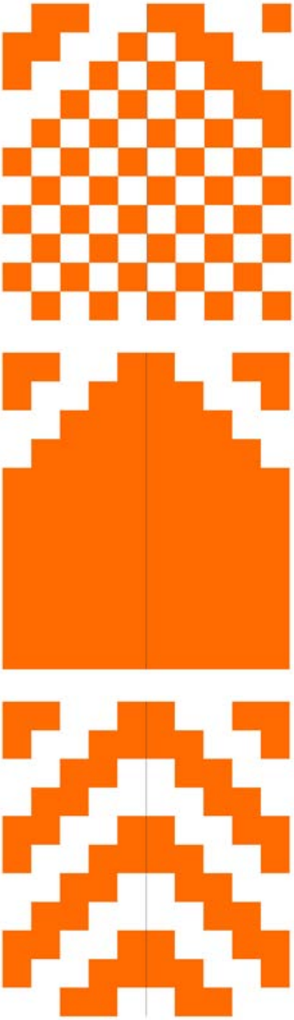
One way to do this is to correct each row as it is generated. For instance, we could decide that if a sequence of five consecutive entries

```
  a(i,j-2), a(i,j-1), a(i,j),
      a(i,j+1), a(i,j+2)
```

all have the same value (either all 0 or all 1), then we flip the entry in the (i,j) position:

```
a(i,j) = 1 - a(i,j)
```

Doing this yields a weaving pattern in which all weft threads are woven into the warp with a spacing of no more than 4 warp threads apart.



(A)

(B)

(C)

Figure 7: *Diverging twill patterns. The middle pattern would yield a poor quality textile and has been corrected in the pattern on the right by disallowing arrangements in which five consecutive entries are identical.*

We can see from Figures 6 and 7 that this simple disruption to a 2-2 twill will result in both converging and diverging twill patterns as well as plain weave (Figure 7A).

Figure 8. *A generative weaving design that incorporates random switching between left and right twill 2-2 patterns.*

In fact, other patterns such as 2-1 and 3-1 twills as well as irregular twill patterns like skip and pointed twills will emerge as the process repeats and columns are chosen at random intervals. In Figure 8 we show a weaving plan generated by this “disrupted twill” algorithm that consists of 100 warp threads and approximately 240 weft threads.

In construction algorithms of this sort, special consideration has to be given to the edges of the design where boundary conditions must be imposed. In the previous example, we approach this issue by using “ghost points” whose values are determined as copies of specific values in the actual row. This is similar to how boundary conditions are often imposed when using finite difference methods to find numerical solutions to partial differential equations [9].

Looms for Generatively Designed Textiles

Looms are machines that automate many of the physical operations required to produce woven cloth. The most essential of these operations are (a) maintenance of uniform tension on the warp and (b) separation of the warp to produce a shed to allow the insertion of the weft. Most looms accomplish the first operation using two horizontal beams: the warp beam, located at the back of the loom, around which all the warp threads are wound, and the cloth beam, at the front of the loom, that takes up the textile as it is woven. The warp is stretched between these two beams and tension is typically maintained using ratcheting mechanisms. This operation of providing uniform tension to the warp, while essential for well-woven fabric, is the easiest to achieve.

The second operation – separating the warp to allow the insertion of the weft – is a more mechanically complex operation. Most looms accomplish this operation using heddles, which are strings or wires that hang vertically in the middle of the loom and which have a small hole through which a single warp thread is passed. These heddles are then variously raised or lowered in different combinations to produce the shed. A number of mechanisms have been designed to facilitate this operation resulting in a variety of loom types.

Typical floor looms use a number of shafts, which are wooden frames that hang vertically and which hold the heddles between their upper and lower members. When an entire shaft is raised, then all of the heddles on this shaft are raised along with it. Hence, one shaft can control any number of heddles, but all the heddles on a given shaft move in unison. To achieve different weaving patterns, then, a loom must have more than one shaft and these shafts must be raised in different combinations; the more shafts, the more weaving patterns are possible. On traditional floor looms, these shaft combinations are achieved using treddles: foot pedals that are tied to the shafts in such a manner that pressing down on one treadle actuates one particular combination of the shafts.

In general, if a loom has n shafts, then it is capable of producing 2^n patterns. This is seen by observing that each shaft can be in one of two positions (up or down) and that the position of any one shaft is independent of the others. However, many of these shaft combinations are not very useful for the weaver. For example, the combination in which all shafts are down (or all up) is useless since it doesn’t produce a viable shed. In addition, even if a loom has many shafts (e.g., 8 shafts which give a maximum of 256 shaft combinations) only a small fraction of these combinations can be actualized by a traditional floor loom since each combination requires a treadle and there is only so much space for treadles. As a result, traditional floor looms are inadequate for weaving generative textile designs.

Some looms that use shafts are actually capable of producing all of their possible shaft combinations. For example, Dobby looms utilize a mechanism that allows any shaft combination to be actualized using a single treadle. Looms of this type have been used to weave generative designs. For example, Visman [4] used a 24 shaft, computer-controlled Dobby loom to weave generative designs inspired by random tilings. A 24 shaft Dobby loom can produce a maximum of 16,777,216 weaving patterns. While this might seem like a lot, it is insufficient for producing most generative designs. For instance, in the previous section we described a simple generative design that requires more than 4^(m/3) different weaving patterns where m is the number of warp threads. For even a coarsely woven textile – like a 40 inch wide rug woven at 4 EPI – this minimum number of combinations exceeds 9 quadrillion. Hence, in order to weave generative designs, a loom is required that is capable of producing a very large number of weaving patterns.

Jacquard Loom

Developed in France in the mid 18th century and patented by Joseph Jacquard in 1804, the Jacquard machine is a mechanism that allows a loom to actuate its warp in any possible pattern. Early Jacquard looms used a complex mechanism of pins and levers controlled by a series of punched cards. Modern Jacquard looms typically use solenoids that are controlled by a computer.

Because Jacquard looms allow any possible weaving pattern to be realized, they are an excellent choice for a weaver who wants to produce complex patterns.

Commercial Jacquard looms are available (e.g., the Jaq3G produced by AVL and the TC2 produced by Digital Weaving Norway), but their price makes them mostly out of reach to the average weaver. A number of different academic efforts have investigated the problem of building lower cost Jacquard-style looms. For example, Ilan Moyer designed and built a desktop loom capable of controlling 24 heddles using electromagnets [10]. Similarly, a team of researchers at Carnegie Mellon Textiles Lab designed and built a low-cost Jacquard loom capable of controlling 40 heddles [1]. M. Benitez and her team from Kent State began a project in 2010 to design a Jacquard loom using muscle wire selectors [11]. While interesting as proofs of concept, the limited resolution of these looms means they are not suited to producing the kinds of textiles that most weavers seek to produce.

We have designed and built a Jacquard loom using low cost components that is capable of weaving full sized textiles at a relatively high resolution (see photo in Figure 9). The heddles of our loom are raised and lowered using off-the-shelf servo motors controlled using an Arduino microcontroller and a chain of very cheap PCA9685 16-channel servo controller boards. Up to 64 different boards can be addressed by a single Arduino and each board controls 16 individual servos. Hence, our loom is capable of independently controlling up to 1024 heddles.

Figure 9: *Jacquard style loom built by the authors. The loom is equipped to control 160-320 heddles and can be expanded to control up to 1024 heddles. The loom base is a 100 year old two shaft rug loom built by Reed Loom Co. Photo by J. Nilan (2023).*

We have built our loom using an old Reed Loom Co. Weaver’s Friend loom as a base to control warp tension and spacing, beating, and cloth take-up. This loom is approximately 100 years old and was acquired for less than $300. The servos are mounted in frames of 80 servos each that are suspended above the loom and which raise and lower the servos in a rising shed style action. More or fewer frames can be added to the loom as needed based on the resolution of the textile to be woven. For our application, we have chosen to produce rugs which require a relatively small number of heddles (between 4 and 8 per inch of weaving width). Hence, the loom we have built, as it currently sits, is equipped to control 160 heddles, which equates to a 40 inch weaving width at 4 warp ends per inch.

Software to control the heddles is written in the open source Arduino programming language. It receives instructions in the form of binary strings (representing the arrangement of each row of the binary matrix weaving design) over its serial port. These strings are parsed to control the action of the servos. As for software to create and store the weaving design as well as communicate with the Arduino, we have chosen to use Mathematica, although almost any “scientific programming” software package could be used instead. For instance, both R and Matlab allow communication via the serial port.

Discussion

Woven textiles featured prominently in the history of art and craft. Rugs and carpets, in particular, have a long history of artistic production, practical application, and cultural significance across nearly every culture and geographic region, both ancient and modern. Looms aid in the creation of woven textiles by both maintaining warp tension and spacing, facilitating the beating of the weft, and most importantly, by creating a shed for the weaver to pass the weft through the warp to facilitate the weaving in various patterns.

Until relatively recently, the patterns available to a weaver were limited by the mechanisms employed by their loom in creating a shed (e.g., the number of shafts available) or else constrained by the time it would take to manually weave complex patterns on looms that could not encode these patterns automatically. Since the invention of the Jacquard loom, however, the ability for weavers to weave complex patterns (indeed, ANY pattern) is unconstrained. While this has led many weavers to exercise a greater control over their weaving patterns, we are interested in the possibilities this brings for artists to relinquish control over their designs by incorporating principles of generative design into their textiles. While several artists have explored this idea, we think there are a lot of discoveries left to be made. We stress, though, that generative design in textile production should always keep in mind the reality of the medium. In this paper, we describe one approach to generative textile design that can result in interesting and well woven textiles.

We have also described a relatively inexpensive method for converting a traditional floor loom to a Jacquard style loom using arrays of servo motors. Though we do not discuss it in this paper, one idea we are excited to explore further is the possibility of digital shaft switching. Shaft switching is a simple mechanism developed by Peter Collingwood [12] that allows a relatively coarse resolution, pixelated block weave pattern to be encoded on a normal 4-shaft countermarch loom using an array of levers. Our Jacquard loom design could be adapted to build a digital shaft switching device using servo motors. This would represent a middle ground between a fully realized Jacquard loom and a traditional floor loom and would allow the weaving of generatively designed textiles without significant expense.

Lastly, we note that while the focus in this paper has been on the abstract structure of textile design, there are many other equally, if not more important considerations in textile design that determine the overall quality of the finished piece. Many of these considerations relate to the properties of the materials used to produce the textile as a physical object. For example, the yarn used for both warp and weft; the balance of the weave; the color of the yarn and how this color is achieved in the dying process; color interactions such as color subtraction and illusionistic space; all of these material considerations affect the final piece in essential ways. We are particularly excited to explore how these material choices and other considerations can be made to work harmoniously with the underlying textile structure.

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