Weaving and Threading Cellular Automata Geometries for Adaptive Architectural Spaces

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Abstract. This study explores the integration of finite-state machines, known as cellular automata (CA), with the process of weaving to create adaptive architectural environments. By focusing on local interactions within CA and using them as a generator, this research examines how the interactions between environmental factors and CA patterns translate into architectural designs through weaving. The bottom-up approach allows for reprogrammable structures responsive to environmental variables, emphasizing soft materials known for complex mechanical behavior suitable for various applications like soft robotics. Weaving, traditionally involving the interlacing of warp and weft threads, is utilized as a CA translator to build intricate three-dimensional structures. The study simulates spatial complexity in discrete environments and provides a framework for creating adaptable structures. This innovative method presents opportunities for flexible and environmentally responsible architectural solutions.

Keywords: Cellular Automata, Weaving, Threading, Patterns, Digital Fabrication

1 Introduction

Finite-state machines (FSMs), or finite-state automata, are mathematical constructs often utilized in the fields of computer science and engineering to define a system's behavior, considering a limited number of states and specific inputs that influence the system's reactions. Within cellular automata (CA) (Wolfram, 2002) (Hoekstra, Et al, 2010), FSMs are arranged in a segmented network, enabling localized connections between adjacent elements. This structure is influenced by geometric patterns emerging from crystal growth simulations, setting the foundation for the organization of atoms at the nano-metric level. This segmented network empowers CA to develop intricate and varied behavioral patterns, where each element can communicate with and affect one another according to its current state and the signals received from neighboring elements. This creates a highly adaptable and responsive system that can evolve with environmental or input changes, enhancing the dynamic and flexible characteristics of CA.

In the nano-metric scale design and organization of systems, FSMs are essential, acting as the cornerstone for organizing the fundamental components in such systems, and their attributes significantly influence their performance and functionality. The geometric patterns produced by crystal growth simulations guide the structure of these fundamental components, managing their mutual interactions and aligning them in a manner that is reactive to both internal structural and external environmental influences. In this study, we delve into the potential of CA as a creator and propagator of patterns, influenced by both external and internal factors. We apply weaving and knitting principles as intermediaries in the activation and deactivation of cells and explore methods of realization using textiles as soft materials in a consistent geometric organization (fig 1.1).

Fig. 1.1 Soft Material simulation over a CA as a continuous geometry. Image from the Authors.

2 CA and discrete points as starting structure

Cellular automata (CA) are fascinating constructs that have found relevance across multiple scientific and artistic disciplines, most notably in the field of artificial intelligence (AI). Essentially, CA systems can be described as self-organizing artificial systems that spontaneously arise from interactions between basic elements, all without human intervention. Unlike conventional systems, these self-organizing systems don't require explicit control or direction from external sources, a feature that has made them indispensable in modeling complex phenomena.

In terms of emergence of complexity from simplicity, the marvel of self-organizing artificial systems lies in their ability to form complex behavior patterns through interactions between simple components, often referred to as agents. These agents, each behaving according to simple local rules, can communicate and adapt based on the system's state. Such behavior leads to the emergence of sophisticated patterns and structures that are otherwise not discernible at the individual component level. Also, these self-organizing systems have been employed to simulate and model intricate systems, ranging from social and transportation networks to entire ecosystems. Moreover, their role in the development of AI and machine learning is noteworthy. They are instrumental in modeling structures like neural networks and genetic algorithms (Risi, 2023), where individual components interact, adapt, and evolve, leading to coordinated and structured behavior despite the absence of central control or direction.

A key aspect of CA is the principle of local interactions or "neighborhood" interactions. In these systems, an individual element, known as a seed, interacts solely with its immediate neighbors, typically those cells in closest proximity to the seed. This system of local interactions gives rise to complex patterns and behaviors, making CA an attractive model for AI systems. In AI terminology, these interactions are often termed "neighborhood interactions," referring to the concept that a single unit or component in an AI system interacts only with a restricted number of other units or components within its immediate vicinity. This notion has significantly influenced the design of numerous AI algorithms, allowing for efficient development of systems that can manage extremely large and complex data sets (Charu & Aggarwal, 2018) (Russell & Norvig, 1995).

Thinking in geometrical representations and neighborhood models, within the realm of CA, neighborhood interactions are frequently depicted within the context of discrete geometric arrays. These represent the specific positions of the components within the system and can take various forms such as regular grids, hexagonal lattices, or other geometric shapes. By defining the neighborhood of each component, the range of interactions within the system is specified. For instance, a "von Neumann" neighborhood comprises the four adjacent components to a central element, whereas a "Moore" neighborhood includes eight adjacent components along with the diagonals (Batty, 2005). These discrete geometric representations offer a robust tool that allows for simulation and analysis of intricate systems, utilized extensively in biological modeling, social network analysis, and the creation of AI algorithms (Bedau, 2003).

2.1 Applications in Architecture and Design

The use of discrete geometric arrangements within cellular automata has not only scientific relevance but has also become an intriguing tool for planning in the architectural field (Batty,1997). CA models have been employed for generating and analyzing intricate spatial patterns within the design domain. By setting simple rules of discrete geometric arrangements, designers can craft complicated spatial structures (Wang,Et al. 2015).

As opportunities in soft materials, finally the exploration of CA extends into the fascinating domain of soft materials like fabrics. By embracing the inherent simplicity and regularity of discrete geometries, opportunities emerge to explore innovative translations of discrete shapes. Since weaving and knitting techniques are fundamentally based on the principles of discrete geometric arrays and local interactions, the translation of CA principles into discrete weaving arrays becomes feasible (fig 1.2). This translation represents an intriguing connection between the positions of the components within the CA system and the tangible realization of these principles in fabric forms.

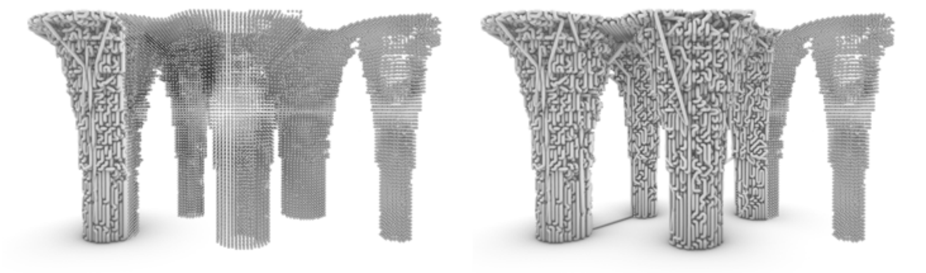

Fig. 1.2 Discrete set of 2D points to be translated by a weaving process. Image from the Authors.

Cellular automata present a rich and multifaceted field with connections to artificial intelligence, design, architecture, and even textile arts. By synthesizing simple components through local interactions, CA can generate complex patterns and behaviors that have found applications across various domains. Their binary nature can both serve as a creative tool and pose potential limitations, emphasizing the need for thoughtful integration with other design methods. The potential application in soft materials offers exciting prospects for future exploration and innovation, linking abstract computational principles to the tactile world of fabrics and textiles.

3 Bridging Discrete Logic and Continuous Forms

Cellular automata (CA) function within a three-dimensional realm and employ a generative method to store the historical evolution within discrete configurations. Accomplished through localized functions that continuously mold and build forms over time by adhering to preset rules, the process is highly abstract and usually binary. Unless interfered with by external or internal factors, which might introduce “noise” into the generative procedure, it remains deterministic (Wolfram,1983)(Herr, Et al. 2015). The present research seeks to move beyond merely representing three-dimensional discrete geometry as an isolated collection of points, lines, and forms. Instead, it delves into methods for conceiving, visualizing, and actualizing connections between these elements. A core objective is to introduce more intricate and refined representations of space that regard the continuous essence of the physical realm, rather than merely a discrete perspective. This necessitates integrating aspects from soft materials, along with other continuous substances like fluids, into the spatial depiction (Gengnagel, Et al. 2018), besides conventional discrete components such as points and lines.

Soft materials, characterized by low stiffness and high deformability, can adapt and change shape in reaction to external forces, such as temperature alterations or electric fields. Examples encompass polymers, liquids, and soft biological tissues like skin or muscles (Gong, 2010). Employed in numerous applications ranging from biomedical devices to soft robotics (Kim, Et al. 2013), soft materials present nonlinear behavior and often manifest intricate mechanical characteristics, rendering them demanding to model.

The growing field of research dedicated to exploring and leveraging the unique features of soft materials is aligned with the research's aim to build spatial complexities using CA patterns (Langton, 1996). The emphasis is on threading continuous structures steered by Synchronous and Asynchronous seeds within discrete settings (Kolatan & Sabin, 2010). The final products of this generative mechanism are then scrutinized as spatial constructions, rendering soft interpretations from the CA's discrete reasoning to elaborate patterns that resonate with the system's complexity demands. In this context, the research specifically targets the construction of woven and threaded translations from the CA system's discrete logic. These "woven and threaded translations" symbolize the conversion of the CA system's discrete logic into elaborate patterns. Generated by imitating the interactions among simple components within the CA system, these patterns are visualized as reactions to the information that governs the system in terms of complexity and density (fig 1.3).

We extends the understanding of cellular automata in three-dimensional space by transcending discrete representations. Through the integration of soft materials and a unique approach to generative processes, it seeks to achieve a more nuanced representation of space. By converting the discrete logic of CA into complex woven and threaded patterns, this work lays the groundwork for practical applications in various fields, including architecture and design. It represents a promising exploration of the intersection between mathematical concepts, physical materials, and spatial design, potentially contributing new insights and methods to multiple disciplines.

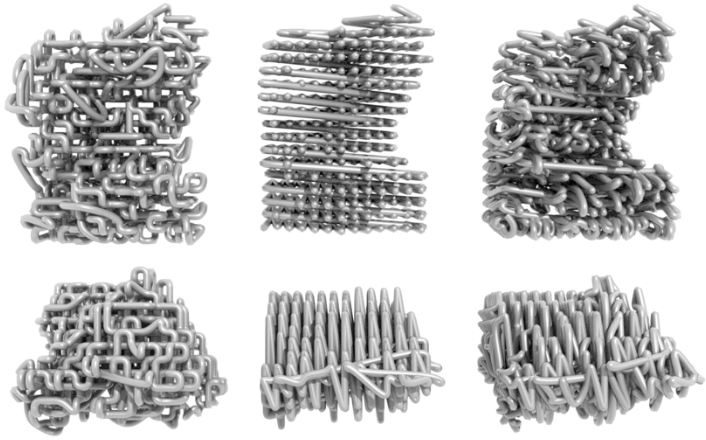

Fig. 1.3 Discrete set of 3D points being translated by a weaving recursive process. (Left), in a linear process (center) and in a mixed variation (right) showing different densities and complexities. Image from the Authors.

4 CA translations using Weaving and Threading

Weaving and threading are fundamental techniques in textile creation, known for their traditional applications. However, the principles behind them go beyond mere fabric creation, having unique parallels with the world of Cellular Automata (CA). Chapter 4 explores this intriguing connection, illustrating how weaving and threading can act as CA translators. Weaving and Threading Explained:

a.- Weaving involves the methodical interlacing of two sets of threads, the warp (lengthwise) and the weft (crosswise), creating a pattern that forms fabric. The warp threads are fixed and remain stationary on a loom, while the weft threads are woven to create intricate designs. Weaving creates flat, two-dimensional fabrics and typically requires a loom to control the process.

b.- Threading, on the other hand, Threading is an essential phase in the process of weaving. Within this technique, the longitudinal threads, known as warp threads, are guided through the loom's heddles or harnesses to form the fabric's underlying structure. This action involves leading every single warp thread through a heddle's eye. The act of threading not only shapes the fabric's pattern and structural integrity but also lays the groundwork for the later interweaving of both the warp and weft threads in the course of the weaving process.

In that sense, the linkage between weaving, threading, and CA stems from the commonality in the foundational principles. CA is a discrete mathematical system, where a grid of cells can take on various states, and transitions between these states are determined by a set of predefined rules. These rules, based on the neighboring cells' states, mirror the repetitive and methodical nature of weaving and threading. This connection extends the traditional applications of weaving and threading, transforming them from mere fabric creation techniques into dynamic tools for translating abstract mathematical principles into physical form (Menges & Reichert 2012).

When we are threading's programmability and its applications, the programmability inherent in threading techniques offers an excellent interface for generating complex emergent forms. By employing computational design, we (as designers) can exert an unprecedented level of control over the fabric's properties while retaining flexibility and adaptability. This innovation has fostered a growing field of research exploring the applications of threading in architectural contexts. With the ability to form various performance levels within a continuous single-form system, threading can enable multi-performative hybrid structures that serve multiple functions and purposes.

4.1 Cellular Automata Patterns in Textiles

The incorporation of CA patterns in textile design introduces a new dimension to the fabrication process. CA models can generate intricate patterns by repeatedly applying simple rules to cells in a grid, mirroring the structure of woven textiles. These CA patterns can be designed to respond to different environmental conditions, such as temperature, humidity, or even user interaction. The result is a set of optimized textiles that can adapt to specific environments, maximizing functionality, comfort, and resource efficiency. The convergence of weaving, threading, and CA opens up prospects for future research and development. By joining the tactile world of fabric creation with the computational power of CA, new tracks are created for architectural design, clothing technology, structural and environmental applications.

Textiles have long been associated with the intricate processes of weaving and threading, where various materials are interlaced to create patterns, textures, and structures (Scott, n.d.). In the context of this exploration, the traditional art of textile fabrication takes a revolutionary turn by employing digital technology and the principles of Cellular Automata (CA). By utilizing the CA XYZ coordinates, the process of weaving and threading transitions from the physical realm into the digital world, providing new ways for exploration, experimentation, and realization:

a.- Creating a Cellular Automata (CA) Point Cloud: To begin, we must generate a CA-based point cloud with XYZ coordinates, which will serve as the foundation for our initial three-dimensional representation of a shape, effectively establishing its spatial constraints. This collection of points will exhibit varying densities, defined by the distances between each point. Subsequently, we will reorganize these points into a specific sequence, culminating in the creation of a spline path that will reinterpret the arranged points, resulting in a woven or threaded outcome.

b.- Digital Threading/Weaving Using CA XYZ Coordinates: The utilization of CA XYZ coordinates offers a distinctive approach to modeling textile structures within a digital realm. Cellular Automata (CA) is a mathematical framework comprised of grid cells that evolve through discrete time intervals based on defined rules. By employing the principles of CA within the XYZ coordinate system, we can create a sophisticated, three-dimensional representation of textiles. This approach facilitates the simulation of intricate patterns, layers, and textures, serving as an initial representation of potential physical outcomes and feasible fabrication techniques, including both traditional 3D printing methods (e.g., FDM, STL) and innovative options like robotic arm printing. This digital methodology empowers precise control, customization, and experimentation, surpassing the capabilities of traditional techniques.

c. 3D Printing of Digitally Threaded or Woven Textiles: Once the textiles have been digitally threaded or woven using the CA XYZ coordinates, they are prepared for conversion into physical forms. The integration of 3D printing technology serves as the crucial link between the digital designs and tangible objects, enabling the realization of these intricate structures. The 3D printer interprets the digital file and meticulously deposits material in accordance with the coordinates and rules established within the CA system. This transformation translates the abstract mathematical principles represented by XYZ coordinates into tangible textiles in the form of physical models, preserving the complexity and intricacy of the initial digital design (Figure 1.4).

The flexibility and programmability of threading make it an attractive choice for designers seeking to explore more adaptable, responsive fabric structures (Ahlquist & Menges 2013). The combination of weaving, threading, and CA offers a fresh perspective on textile creation, redefining it as a fusion of art, craft, and technology. It sets the stage for the development of intelligent fabrics, capable of adapting and responding to their surroundings, laying the groundwork for further inquiry and innovation (like Knitting), expanding the boundaries of what's possible with fabric, threads, and mathematical principles.

Fig. 1.4 Discrete set of 3D points being translated by a weaving recursive process, showing different densities and complexities. Image from the Authors.

5 Methods: Merging CA Logic with 3D Textiles

The world of textiles, historically confined to 2-dimensional planes, has entered an unprecedented phase of innovation, transcending their conventional boundaries by delving into how Cellular Automata (CA) logic can be adapted to a 3D environment and coupled with generic threading machines (Banerjee, 2014). It uncovers the potential of digitally threaded or woven textiles using the CA XWZ coordinates, 3D printing, and exploring the results through renders and 3D models.

a.- Step 1 Exploring Generic Threading Machines and CA Logic: Generic threading machines stand out as versatile devices that weave threads or yarns into fabrics, unlike specialized machines that are confined to specific patterns. These machines intertwine threads based on predetermined sequences, forming fabrics with varying textures and patterns. The traditional threading process is now augmented with CA logic. Cellular Automata are discrete mathematical models where simple rules dictate the state of each cell within a grid, influenced by the states of neighboring cells. In the context of a threading machine, CA logic translates into specific threading commands, such as loops, knots, or crossovers, enabling a generative process that produces intricate patterns.

b.- Step 2 Digital Threading and Weaving with CA XYZ Coordinates: Employing the CA XYZ coordinates, the process of threading and weaving is transitioned from the physical to the digital realm. This 3D coordinate system facilitates complex representations, allowing for the creation of layered patterns, textures, and structures. The digital threading method leverages the principles of Cellular Automata to simulate the traditional weaving process, but with an added dimension of complexity and control. It harnesses the power of CA's deterministic nature to explore novel textile configurations, bridging the gap between theoretical modeling and practical applications.

c.- Step 3 Translating CA Patterns into 3D Printing: By translating CA patterns into threading commands for 3D printing, designers can now physically realize their complex digital designs. The intricacy of the CA-driven patterns is maintained in the 3D printed textiles, reflecting the convergence of computational logic and creativity. The final products, visualized through renders and materialized in 3D models, offer an innovative means to gauge the efficacy of this method in creating multi-dimensional architectural space. It signals the potential for employing this approach as a practical tool for designing and constructing real-world structures across various scales.

6 Conclusions

The exploration detailed in this research delves into the nexus between digital algorithms, specifically Cellular Automata (CA), and the age-old practices of weaving and threading. In this fascinating intersection, the weaving and threading process has been harnessed to represent the emergent patterns stemming from CA rules. What emerges from this novel approach is not mere fabric but complex, three-dimensional structures that reveal an intricate interplay between discrete logic and continuous geometry.

The implications of this exploration go beyond aesthetics. By probing and testing these physically translated structures for attributes like load resistance, the research lays bare the profound relationships between mathematical abstraction and tangible form. This methodology thus becomes a conduit for expanding the understanding of both digital algorithms and physical materials.

The focus of this research is not confined to theoretical insights alone. The aim extends to practical application, as the research explores the potential of the interrelationships between CA rules, environmental conditions, and the geometric patterns born of weaving and threading processes to forge architectural spaces across various scales. The architectural innovations presented in this research are underpinned by an intricate system of rules and interactions dictated by CA. The resulting complex structures have the potential to redefine architectural spaces, making them not just functional but also responsive, adaptive, and aesthetically engaging.

The success of the integration of CA with weaving and threading techniques lies in the creation of dynamic structures that can interact with and respond to their environment. The researchers have uncovered innovative ways of designing and constructing spaces that resonate with the surroundings, changing and adapting in harmony with fluctuating conditions. Combined with the principles of CA, flexibility and deformability contribute to the creation of reprogrammable structures that evolve and adapt in response to environmental cues.

Self-Organizing systems are a foundational aspect of this approach, with emphasis on local interactions and environmental responsiveness. It fosters a bottom-up design philosophy, where rules within the system can be activated or deactivated in response to external information. This has led to the pioneering idea of self-organizing systems, capable of continuous adaptation and evolution. Such systems are not confined to architecture alone. The principles elucidated in this research have far-reaching applications in fields as diverse as engineering, robotics, and beyond.

As a future perspective, the synthesis of cellular automata and soft materials has forged a pathway towards self-organizing structures, responsive to their environment, and capable of evolution over time. The incorporation of ancient techniques like weaving and threading into this approach enriches the resulting structures with an organic complexity. The possibilities that this research unleashes are boundless. The innovation and insights gained have the potential to not only redefine architectural design but also spur advancements in various interdisciplinary fields. As this line of inquiry continues to evolve, it holds the promise of continually reshaping our understanding of design, space, and the symbiotic relationship between digital and physical realms. In essence, the marriage of cellular automata with weaving and threading has ignited a new era of dynamic, adaptive, and self-organizing design that resonates with the living world around it.

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