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Flexible Earth-Fiber Structures in 3D Printing

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Abstract

3D printing has been shown to offer greater geometrical accuracy and production efficiency for textile and fabric-like structures. However, current 3D printed textiles have been exploring 3-dimensionality of lattice flexibility, mostly using petroleum-based material mixtures such as PLA (polylactic acid). Natural earth- and bio-based materials are minimally processed and use natural substances that may mitigate carbon intensities by reducing the amount of thermal and chemical processing. Specifically, with earth-based materials as an emerging research direction in additive manufacturing, deposited layers of material can create lattice objects. This paper presents a novel development that uses earth-fiber mix designs to create digital techniques for 3D printable flexible structures. Using a range of patterns and geometries, the 3D printed textiles were designed to exhibit a range of densities and patterns. Geometrical tectonics were applied using the mechanism of weaving (wefting and warping) to the different iterations that were created in this research. Material mix-designs were shown to heavily influence the resulting performance of the fabric. The findings demonstrate the capability of producing flexible soil-fiber flexible structures with characteristics akin to traditional knitted textiles, emphasizing promising prospects for further advancement and practical application of natural materials into architectural and wearable artifacts.

Introduction to 3D printed textiles

Fabric is a flexible, woven, knitted, or non-woven material composed of fibers that are entwined together to form a cohesive structure (Kumar and Hu, 2018). It is a textile product that serves as a basic building block for various everyday items, from wearable garments to architectural finish materials. In the context of 3D printed fabrics, the term "fabric" is used loosely to refer to structures that may not resemble traditional textiles. These structures can range from flexible and intricate lattice-like patterns to more rigid forms, depending on the intended application and the materials used.

Research on 3D printed fabrics, such as woven sheets (Kumar and Hu, 2018) or chain-mail armours (Bradley, 2015), were shown to derive their properties both from the constitutive materials and their geometry. 3D printed fabrics are created layer by layer through additive manufacturing processes. These fabrics can exhibit intricate and customizable designs, as well as unique structural properties. The materials employed in 3D printed fabrics can include plastics, polymers, elastomers, metals, ceramics, and even composite materials. Chain-mail fabrics, shown in Figure 1, were previously produced in Caltech with a nozzle system and turntable that allowed the 3D printing machine to flip the print and thus produce looped and interlocking patterns (Wang et al., 2021).

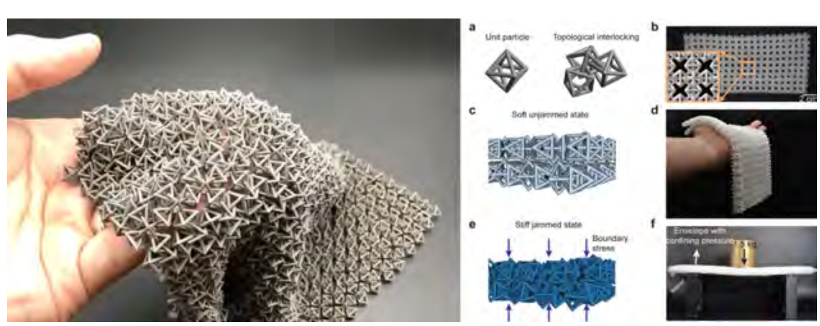

Figure 1. 3D Printed 'chain-mail' fabrics made with PLA (polylactic acid), and interlocking configuration (Source: Wang et al., 2021)

The method of 3D printing yields the fibers to be arranged in a three dimension configuration to create a structural framework or reinforcement within a material (Yu et al., 2021). Reinforcing materials with integrated 3D structural fibers were shown to

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offer superior performance due to their ability to distribute loads and stresses in multiple directions. This results in enhanced strength, stiffness, and damage resistance in the final composite materials (Compton and Lewis, 2014). 3D structural fibers were also shown to enable anisotropic properties in composite materials, meaning, the mechanical characteristics vary based on the direction of load application (Ma et al., 2019). The anisotropy of the object can be, therefore, tailored to suit the specific requirements of the use or material application (Ma et al., 2019).

Common materials for 3D printing, and specifically, additive manufacturing techniques, use predominantly PLA (polylactic acid), which is claimed to be a biodegradable plastic (Flynt, 2020). Man-made fibers, such as nylon, glass, and carbon fibers are also commonly utilized in 3D printing to enhance the mechanical properties and performance of materials in various applications. These synthetic fibers are engineered to provide specific characteristics and can be incorporated into different binders to create composites with improved tensile strength and durability (Yu et al., 2021).

Figure 2. Fiber orientation within an ink (Source: Compton and Lewis, 2014); High degree of material orientation in the printing direction (Source: Yu et al., 2021)

The utilization of natural materials in 3D printing is still relatively limited compared to synthetic materials. While 3D printing has seen significant advancements in recent years, the majority of materials used in the process are synthetic polymers and metals. However, there has been growing interest and ongoing research in incorporating natural materials (such the use of soil and organic fibers) into 3D printing to address sustainability and environmental concerns (Rossi et al., 2019; Bryson et al., 2022; Akemah and Ben-Alon, 2023). Due to the infancy of using natural materials in digital techniques, 3D printing with natural materials may require specialized extrusion methods and processing techniques due to their unique compositions and characteristics. Natural materials can have variations in their properties and composition, which can affect the material consistency and reliability of the 3D printing process.

Given these opportunities, the main objective of this study is to develop geometrical tectonics for earth-fiber textiles to create a flexible substrate that can be 3D printed for wearable and building-application scales. By doing so, this research aims to catalyze a radically low-carbon fabric production mechanism by utilizing raw and readily available substances. Specifically, this study asks the following questions:

- What are the optimum 3D printing processing parameters for the earth-fiber mixture, including layer height, printing pace and speed, extrusion flow?;
- What is the structural tearing capacity of different geometries considering digital weaving protocols?

Methodology

This research employs a 3D printing process that commences with a digital model, crafted in modeling software, Rhinoceros 7 (Robert McNeel and Associates, 2023), and further processed via a slicer to generate a g-code file, containing geometric data. The material is subsequently loaded and extruded using a PotterBot 10 Pro 3D printing machine (3D Potter, 2023), with configured printing parameters, including nozzle size, speed factor, extrusion factor, and layer height.As depicted in Figure 3, the experiments are assessed based on their visual characteristics and structural outcomes. Three geometrical iterations were tested for performance analysis: (1) plain weaving; (2) plain weaving and (3) knitting pattern.

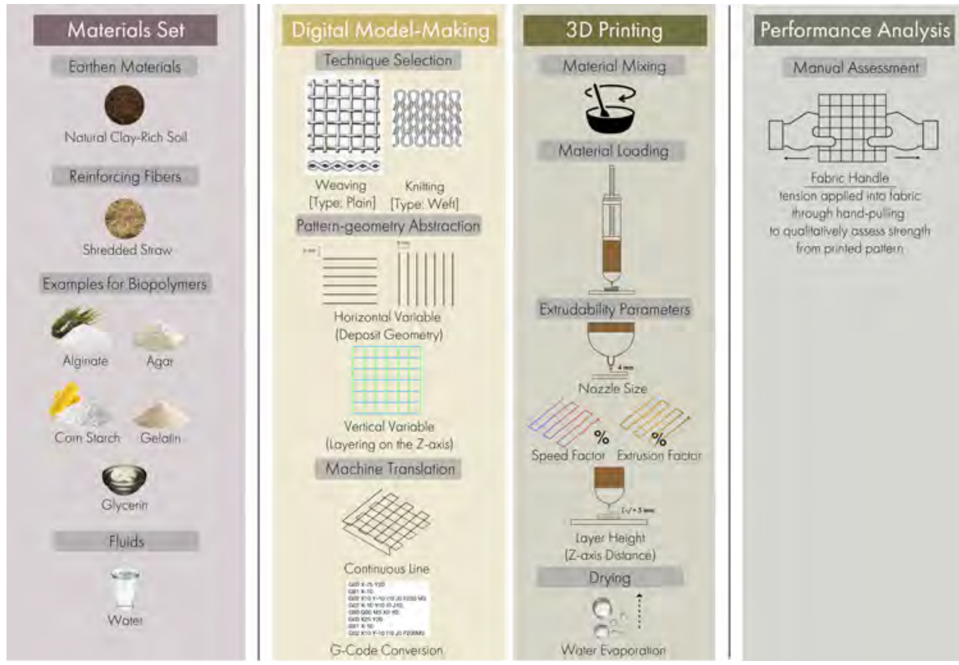

Figure 3. Research Methodology Diagram

Materials Set

The soil used in the fabric comes from the Hudson Valley, which typically consists of brown-grey loam with approximately 10 % of clay content. Wheat straw was introduced into the mixture as a reinforcing element, alongside food-grade polysaccharides that served as stabilizing agents.

Geometries

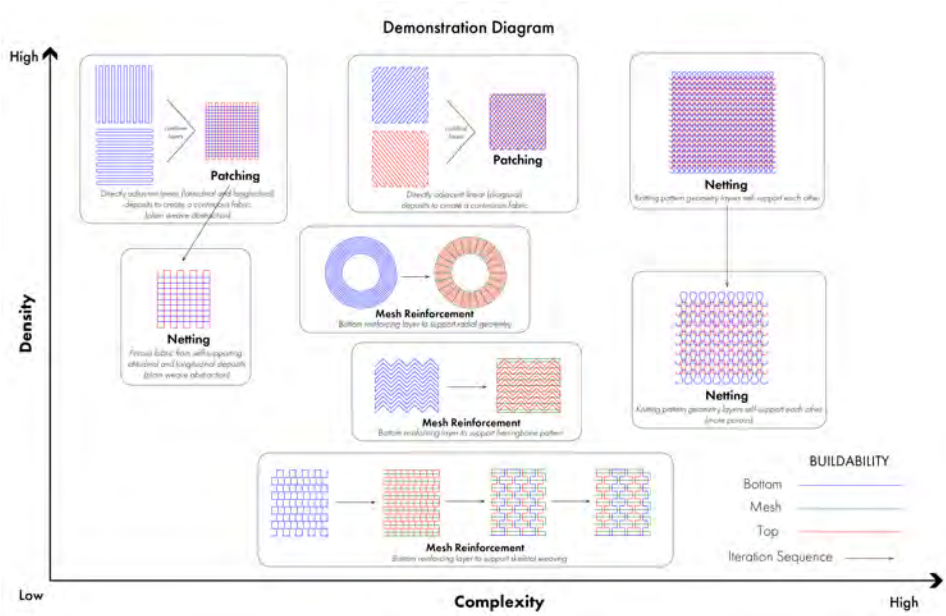

Figure 4. Demonstration Diagram

Several geometric iterations were explored (Figure 4) to test its different mechanical and structural characteristics. The methods of patching, netting and mesh reinforcing

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were applied from abstracting weaving mechanisms - where different layers correspond to either wefting or warping. The geometries are categorized based on their density and complexity. The density describes the number and distance of line deposits in a given square unit of the fabric.

Complexity is defined as the intricacy resulting from the pattern arrangement or repetition of various elements. Iterations were developed based on the printing trials of different layers and combining them to develop the buildability of the fabrics. For example, in the mesh reinforcement skeletal weaving iteration, each layer corresponds to an element of structural support, and considering the low density of the pattern, the different layers are expected to converge into one layer to form a fabric.

Performance Analysis

The resulting prints were subjected to a qualitative visual assessment. Hand-pulling was employed to gauge the extent of the fabric's deviation from its initial pattern. The resulting prints were evaluated through manual application of 1) lateral tensile force, 2) longitudinal tensile force, 3) top-left, bottom right tensile force and 4) top-right, bottom left tensile force.

Results and Discussion

The outcomes of the fabric printing show the iterative development of the 3D printed textures. Each iteration of the resulting prints shows its own structural and functional properties. Resulting prints of the geometrical iterations in the Plain Weaving samples (Figure 5), Knitting Pattern samples of lower density (Figure 6) and higher density (Figure 7) and Skeletal Weaving samples (Figure 7) show the buildability of fabrics made with two layers on the z axis and the resulting printing and texture consistencies.

Figure 5. Demonstration of Plain Weaving samples

Figure 6. Demonstration of Knitting Pattern samples, showing different arrangement of the resulting fabrics

Upon printing on two different substrates (wherein the substrates acted as another Z-axis and structural variable), it is shown (Figure 8) that printing on the Biomud fabric

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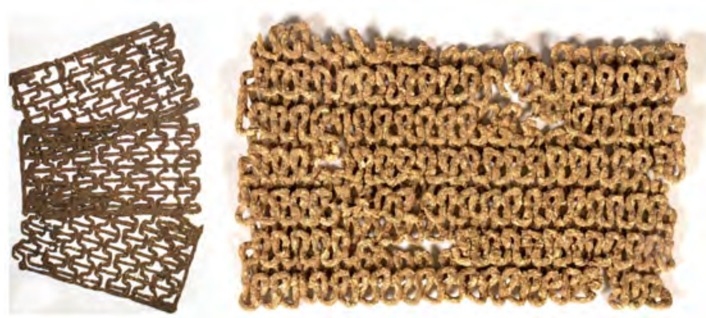

Figure 7. Demonstration of Skeletal weaving pattern (left); Demonstration of Knitting Pattern but with higher density (right)

was more accurate, where the resulting print was the closest to the digital pattern. The resulting print on top of the jute fabric (Figure 8) was less accurate, as the weaved jute substrate added to the unpredictability of the layer height needed to create a print as close to the digital pattern as possible.

Figure 8. Demonstration of printing in two types of substrates - Biomud fabric (left) and weaved jute fabric (right)

Figure 9 shows the application of Skeletal Weaving (mesh-top layer combination), highlighting the inherent flexibility of the pattern. These prints have the potential to be utilized in various ways, such as crafting wearable garments that can offer ergonomics and aesthetics, as well as integrating them into architectural elements to introduce a dynamic and functional dimension to structural designs.

During the drying process, it is observed that the deposits of soil mixtures shrink due to moisture evaporation. Figure 10 shows the comparison between pre-drying and dried state of the resulting print.

The findings in Figure 11 reveal insights into the qualitatively assessed flexibility of the different fabric patterns. Among the patterns assessed, the Plain Weave stands out with the highest overall strength and minimal deviation from its original pattern. However, its weakness lies in its diagonal strength. On the other hand, the Skeletal Weave exhibits the lowest strength among the tested weaves and displays the most significant deviation from its original pattern. Similar to the Plain Weave, the Skeletal Weave also demonstrates weakness in diagonal strength. The Knitting Pattern falls in the middle in terms of strength, displaying a moderate lateral/longitudinal strength, showing medium resistance to tension. However, akin to the other patterns, its diagonal strength remains

Figure 9. Demonstration of Skeletal Weaving (mesh-top layer combination), showing the property of resulting prints, where its flexibility can be applied as wearable garments and architectural elements

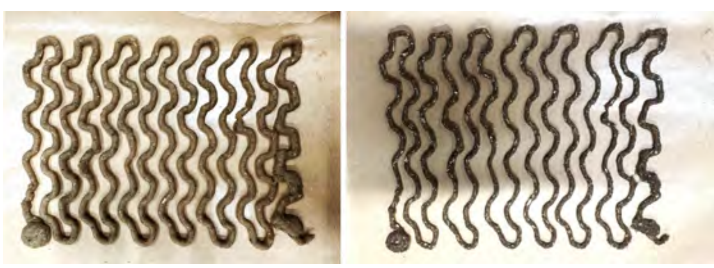

Figure 10. Demonstration of shrinkage of line deposits after drying

weak. These findings depict the varying performance attributes of different fabric patterns and can inform geometric selection for the fabrics for its applications.

The density of the geometries is shown to be the main factor that contributes to the fabric strength. The more line deposits that are closer to each other, the more resulting fiber touchpoints are carried by the soil-mixture. The density also presents the ability to build another pattern vertically on top of the existing one.

The mechanical characterization of the soil-fabrics reflect the ratio of the materials, particularly the ratio of glycerin in the mixture. The addition of glycerin contributes to the flexibility and smoothness of the fabric texture. When less glycerin is added, the resulting fabric was shown to be more stiff. The layer height (z-axis distance) also presents as a factor to the flatness of the resulting printed fabric. As the layer height decreases, the soil-mixture is distributed by the extruder more flatly.

Conclusion

Research on 3D printed soil-based fabric represents a groundbreaking endeavor still in its early stages of development, especially in the realm of bio-based materials in printing. By harnessing additive manufacturing techniques, the study not only explores the creation of earth-based fabrics through the mix of digital and analog methods but the investigation also delves into multiple fabric iterations, unveiling the feasibility of producing soil-based textile fabrics with considerations for density, buildability, and substrate usage.

The interplay between soil, fibers, biopolymers and moisture in the material mixture significantly influences the fabric's structural characteristics, leading to the realization of intricate geometrical tectonics through weaving (through the abstraction of the wefting,

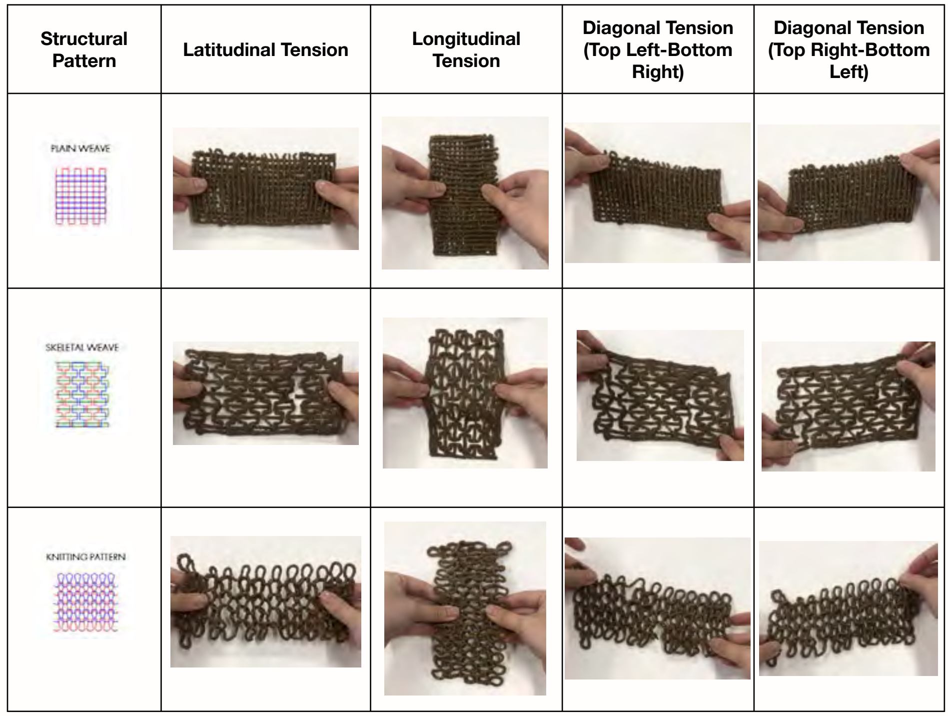

Figure 11. Results of Performance Analysis through Fabric Handle

and warping mechanisms). The integration of historical weaving patterns adds an intriguing aspect to the research – the findings reveal the exciting possibility of producing flexible soil-based fabrics that possess qualities reminiscent of traditional knitted textiles, while embracing the mechanical properties of the employed materials. Nevertheless, the study acknowledges the challenges in achieving fine printing resolution, an area that requires further exploration and refinement.

This study catalyzes new avenues for sustainable and nature-based textiles. Looking ahead, the promising prospects of these creations hold great potential for future advancements and practical applications. Envisioning 3D printed fabrics, incorporating both bio-printing methods and traditional components, worn as garments and employed for facades and sun-shading devices in architectural settings, this research paves the way for innovative possibilities in the realm of sustainable and bio-integrated textiles.

Data availability statement

The authors will provide the data upon request.

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Conflict of interest

The authors have no conflicts of interest to declare for this publication.

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