

A fabrication-oriented remeshing method for auxetic pattern extraction

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Abstract: We propose a method for extracting auxetic patterns from meshes for fabrication by modifying the existing mesh primitives directly and fully automatically. This direct approach is novel in the sense that most of the fabrication-oriented surface tiling methods introduce additional primitives, such as curve networks in an interactive semiautomatic framework. Our method is based on a remeshing procedure that converts a given quad mesh with arbitrary topology into our desired structure that is ready to be fabricated. The main advantages of establishing auxetic patterns on meshes are the achieved flexibility using cheap inflexible materials as well as less material usage and fabrication time, as demonstrated in our results.

Key words: Auxetic, texture synthesis, filigree synthesis, geometry processing, 3D printing, digital fabrication

1. Introduction

3D printing is a trending technology for fabricating physical three-dimensional objects from digital designs. Nowadays, 3D printers are widely used in various fields from homes to industry and they can work with a diverse set of materials. These materials have different flexibility characteristics. If an elastic object is desired as the output of a 3D printing session, the material used by the 3D printer is typically an elastic material that is more expensive than a regular polyactic acid (PLA) filament.

3D printers merely print the digital designs with specified materials without any awareness of the digital designs' flexibility. Digital designs, however, can be modified to behave elastically when they are 3D printed even though the material used during the fabrication is not sufficiently, or at all, elastic. This can be done by changing the surface of the digital design with consistently connected auxetic patterns. The term auxetic refers to structures that have negative Poisson ratios. These structures bring flexibility and elasticity to the objects regardless of the material they are printed with.

Replacing surfaces of digital designs is a popular topic in computer graphics. Many types of research have been conducted on this topic for different purposes and obtaining 3D printed elastic objects is only one of them. Various complex methods are proposed to change surfaces of digital designs in order to fabricate them and obtain elastic objects with inelastic cheaper materials.

Fabrication of the auxetic structures is another subject for computer graphics as they are vacuolar structures that are not trivial to print. Fabricating vacuolar structures vertically is challenging without using internal support structures. If internal support structures are employed, however, then the obtained 3D printed object is likely to deviate from the original digital design.

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1.1. Motivation and contributions

We are motivated to bring the aforementioned benefits of auxetic structures to digital designs, and by fabrication to the physical end products. To this effect, we propose a simple novel method to extract auxetic patterns from digital designs that come in the form of quad meshes. We also propose a way to fabricate these extracted auxetic patterns. Such a fabrication creates elastic objects with inelastic and cheaper printing materials. Additionally, we apply the proposed algorithm for the generation of flat digital designs consisting of auxetic patterns, which can then be wrapped around complex 3D physical shapes. Thanks to the vacuolar structure of our end result, we also reduce the material usage as well as fabrication time. To summarize:

- In contrast to many pattern synthesis techniques that introduce additional primitives such as curve networks, we modify the existing mesh primitives into auxetic patterns directly and fully automatically. To this end, a novel auxetic pattern extraction algorithm is designed for quad meshes that has arbitrary topology, e.g., closed, open, high genus.
- Simple flat shapes consisting of auxetic patterns are generated in order to wrap up complex shapes, resulting in an alternative way to create auxetic patterns on arbitrary 3D shapes.
- Elastic fabrication is achieved by using auxetic tiling of inelastic and cheap material.
- The vacuolar structure of our auxetic patterns enables less material and time usage during fabrication.
- The source code, executables, output meshes, and output codes for the method that we present in this paper will be publicly available on the authors' website.

2. Previous work

Texture and filigree synthesis for fabrication is an important topic in computer graphics and consequently draws significant attention from the community. Although these studies can be categorized into separate classes such as visuality, flexibility, cost-effective manufacturing, and fast prototyping, they try to achieve the same task: replacing the objects' surfaces with patterns. As a pattern synthesizer method, we investigate the extensive related research in the fabrication domain in these restricted categories. We also provide the application areas of the auxetics. A comprehensive survey on various 3D printing aspects can be found in [1].

2.1. Studies on visuality

The aesthetic appearance of digital models is quite important in computer graphics as these models lend themselves to subsequent processes such as video games and fabrication. There exist many studies about texture synthesis, which enhances the aesthetic appearance. Ma et al. [2] conducted an extensive survey on texture synthesis methods. Different methods were designed for image-based texture synthesis such as covering the target surface with patches [3] and mapping texture directly on the target surface [4]. Zhou et al. [5] also designed a method named mesh quilting for geometric texture synthesis. Ma et al. [2] developed a data-driven method for synthesizing large domains with small input textures. Garg et al. [6] presented an approach to design meshes consisting of woven wires. Their approach combines small wires woven in a plain weave to create wire meshes that represent large objects.

Torres et al. [7] stated that haptic characteristics that contribute to aesthetic value are generally lacking in 3D printed objects. Therefore, they created a tool for mapping texture elements onto objects for 3D printing.

Dumas et al. [8] also synthesized patterns that are not only fully connected but also structurally stable for 3D printing along surfaces. Additionally, Chen et al. [9] managed to automatically synthesize a set of inputs creating filigrees together for target surfaces of objects. Their automatic filigree creation results are also 3D printable. Furthermore, a tool for designers was created by Schumacher et al. [10] in order to generate surfaces structured with decorative patterns. The user specifies the decorative pattern and target shape and the tool covers the target shape with the given decorative pattern while considering the target shape's durability. Therefore, the target shape with covered decorative pattern can be 3D printed. Zhender et al. [11] also developed a tool for designing ornamental surfaces consisting of curve networks. Their tool admits user-defined spline curves as an essential design parameter. Therefore, the user can control the aesthetics. Besides, their tool considers the soundness of the surfaces for 3D printing.

Zhao et al. [12] took a different perspective. They focused on how to efficiently 3D print objects synthesized with patterns. They suggested synthesizing surfaces with connected spirals, which can be fabricated without on-off switching of the print nozzle. Their approach ensures continuity of the nozzle path during the 3D printing operation.

2.2. Studies on controlling elasticity

Elastic models appear in many computer graphics applications ranging from deformation [13] to nonrigid correspondence [14]. It is also a desirable feature in real-world models such as toys and tools. Some of the related fabrication methods proposed approaches to modeling objects as networks of elastic rods [15] and packable springs [16]. Perez et al. [17] created a tool for 3D printing of deformable objects consisting of rod meshes. Their tool gets a deformable object and a set of deformed poses of it and generates a 3D printable rod mesh that resembles the input object. When the generated rod mesh is 3D printed, it exhibits the desired deformation.

Panetta et al. [18] designed a pattern family consisting of small structures that are 3D printable with a single material and without internal supports. Their patterns are also elastic. They can combine these small patterns from their designed pattern family in order to fabricate large objects having desired mechanical behaviors. Similarly, Schumacher et al. [19] proposed a method for 3D printing objects having different elastic properties at different parts. They generated microstructures to control elasticity at different parts of the objects. Their method allows the printing of 3D objects consisting of these microstructures and demonstrates varied elastic properties at desired parts of these objects with a single material. Additionally, Martinez et al. [20] used microstructures inspired by Voronoi open-cell foams for creating 3D printed elastic objects. They allow the user to specify elasticity on different parts of the model. Then they generated the corresponding structures in order to provide these elasticities. These generated structures also can be 3D printed directly.

Konakovic et al. [21], Guseinov et al. [22], and Schumacher et al. [23] also have methods to design elastic objects from fabricated flat surfaces consisting of patterns that provide elasticity.

2.3. Studies for cost-effective fabrication

One of the biggest issues in 3D printing is the material cost. Because of the high material costs in 3D printing, Wang et al. [24] came up with the idea of 3D printing skin-frame states of objects. They developed a method for automatically designing skin-frame states of objects. Their skin-frame structures resemble the seed objects used in production. These structures are also proper for 3D printing. Moreover, these structures reduce the printing material to be used. Lu et al. [25] designed a hollowing optimization method for generating honeycomb-like

structures inside the objects in order to reduce material costs in 3D printing. Their resulting fabrications are also highly durable.

2.4. Studies for rapid fabrication

Another important issue in 3D printing is the fabrication time. Mueller et al. [26] addressed the long fabrication time issue by proposing 3D print wireframe previews instead of the objects. In other words, they replaced the objects' surfaces with wireframe meshes and then 3D printed them. They modified a 3D printer in order to 3D print these wireframe meshes because traditional layer-wise additive manufacturing was not suitable to 3D print edges of the wireframe meshes. Their modified 3D printer extrudes material directly into 3D space and uses extra cooling mechanisms while 3D printing edges of wireframe meshes.

Peng et al. [27] advanced the 3D printing wireframe meshes and provided on-the-fly 3D printing opportunities for designers. Their system is integrated with CAD/CAM software used in the creation of digital objects. The digital objects are analyzed by their system and turned into the appropriate wireframe meshes. These wireframe meshes are 3D printed in parallel. Changes to the digital objects are immediately reflected in the 3D print process.

Wu et al. [28] took wireframe 3D printing technology one step further with their 5DOF wireframe 3D printer. They developed a method for generating 3D printable (by using their 5DOF wireframe 3D printer) wireframe meshes of arbitrary meshes. Their 5DOF wireframe 3D printer can rotate the print during 3D printing operation if it is necessary. Thus, any edge of the wireframe mesh can be 3D printed.

3. Auxetic pattern extraction method

3.1. Selected auxetic pattern

We pick the reentrant honeycomb structure as our auxetic pattern. Figure 1 shows this structure.

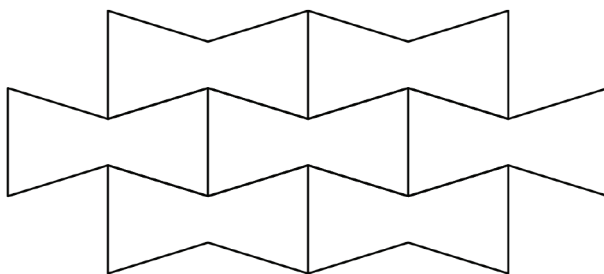


Figure 1. Reentrant honeycomb structure as our auxetic pattern.

The reentrant honeycomb pattern consists of hexagons. The structure of a hexagon is proper to exhibit auxetic behavior. When a tensile force is applied to the hexagon, it enlarges in a parallel direction to the applied force's direction. The auxetic behavior of a hexagon can be seen in Figure 2.

The reentrant honeycomb pattern is chosen as the auxetic pattern because the hexagons creating this pattern can be derived easily from properly combined quads. This enables direct remeshing of a quad mesh into an auxetic mesh. The main idea is to extract the hidden hexagons from the hosting quad mesh in a consistent manner. Consistency ensures the correct connectivity between the neighboring hexagons. Two quads having one common edge are associated with a hexagon shape as shown in Figure 3a.

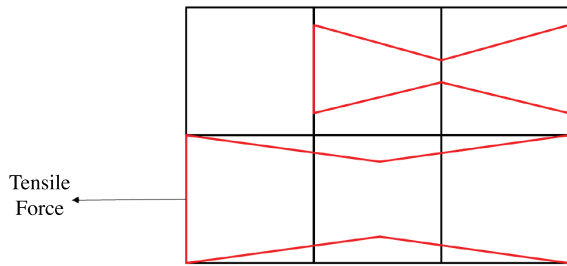


Figure 2. Hexagon and its enlarged form after the application of a tensile force. Notice both the horizontal and vertical enlargements.

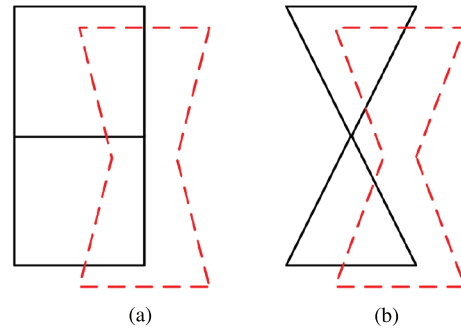


Figure 3. (a) Properly combined quads yield hexagons. Merging operator attracts the endpoints of the shared edge, which is then removed. (b) Properly combined triangles yield hexagons. Merging operator creates the copy of the shared vertex and two vertices then repulse each other.

3.2. Extracting auxetic patterns from quad meshes

We prefer quad meshes over triangle meshes due to the natural isotropic flow of the former. Our extraction algorithm can be extended to triangular meshes seamlessly and easily based on the new merging operator shown in Figure 3b. This would, however, typically suffer from the tilted or sheared auxetic patterns as shown in Figure 4. Notice that even a regular triangle mesh plane, such as the one in Figure 4a, is not suitable to extract isotropic auxetic patterns that have a uniform flow over the input plane mesh. We observe an undesired anisotropic behavior that emphasizes a particular direction, which in turn causes problems after fabrication, e.g., output print bends towards those directions.

Having established the necessity of the quad meshes for our purposes, we now introduce our auxetic pattern extraction algorithm. Starting from an arbitrary quad q in the mesh, we need a second quad r in order to create the pair to be converted into a hexagon as depicted in the merging operation of Figure 3a. The attraction amount used in merging for the endpoints of the shared edge is $\frac{3}{8}$ of the shared edge's length. Additionally, the endpoints of the opposite unshared edges have to be attracted because they would help create internal hexagons that connect the surrounding hexagons. The attraction amount for the endpoints of the unshared edges is $\frac{1}{8}$ of the unshared edges' lengths. The hexagon creation process with respect to these attraction amounts is shown in Figure 5.

For r , we randomly pick one of the four alternatives that are neighbors to q through an edge. With no loss of generality, suppose that we pick the left one, creating a horizontal hexagon, or bow tie as we refer to it from now on. We then proceed by propagating towards the vertical direction until we close the loop of bow ties or we cannot find the next bow tie. Then we move to the bow tie at the left or right of the first bow tie and start the next vertical stripe of bow ties. We proceed in this manner recursively until the whole shape is covered, i.e. all quads are visited by these propagations. To increase the robustness, we reinitialize this procedure with a new arbitrary quad q multiple times and select the execution, which yields the maximum number of bow ties and hence the maximum auxetic coverage. Finally, we create internal bow ties standing between found bow ties with the same recursive approach.

Our extraction algorithm is shown in Algorithm 3.1. Functions FINDBOWTIES and FINDINTERNALBOWTIES are recursive parts of our algorithm. These functions create bow ties as described above. Full

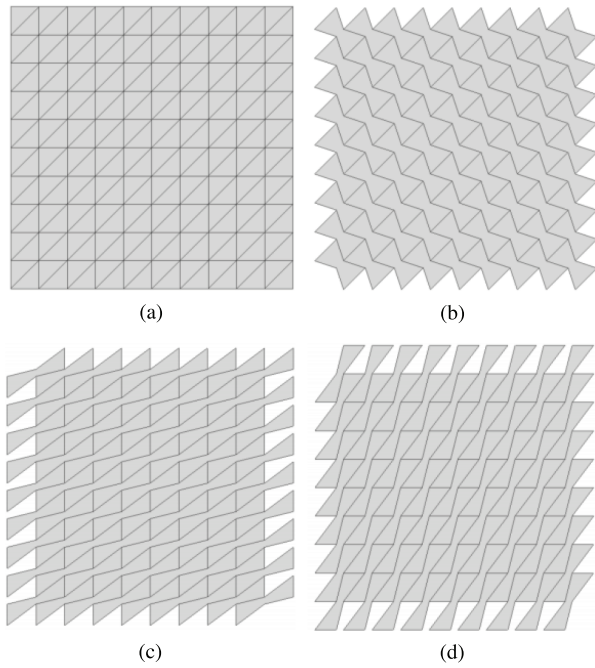


Figure 4. (a) A regular triangle mesh producing tilted results when elements to be merged are selected (b) diagonally, (c) horizontally, and (d) vertically.

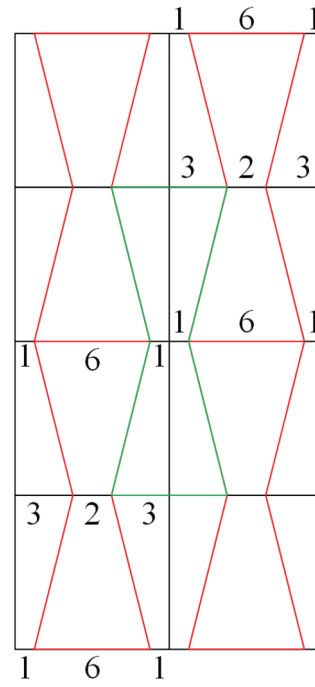


Figure 5. Each of the four hexagons (red) is created by the merging of its two hosting quads. An internal hexagon (green) connects two sets of hexagons, in this case connecting the vertical stripes consisting of two hexagons at left and two at right.

detail is provided in the form of pseudocodes in our supplementary material, which also includes a step-by-step execution trace for further clarification.

Algorithm 3.1 SEARCH(QuadMesh, StartingQuad).

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1: BowTieMesh = empty set of bow ties, their points, and their edges
2: QuadNeighbors = quads having a common edge with StartingQuad
3: Write QuadNeighbors
4: Read PairQuad
5: FINDBOWTIES(BowTieMesh, QuadMesh, StartingQuad, PairQuad)
6: for each quad Q ∈ QuadMesh do
7:   if Q.IsMatched then
8:     QuadNeighbors = quads having a common edge with Q
9:     for each neighbor quad NQ ∈ QuadNeighbors do
10:      if !NQ.IsMatched and Q is the only neighbor of NQ that is matched then
11:        NewStartingQuad = NQ
12:        NewPairQuad = GETOPPOSITESIDENEIGHBOR(QuadMesh, NewStartingQuad, Q)
13:        if NewPairQuad ≠ null then
14:          FINDBOWTIES(BowTieMesh, QuadMesh, NewStartingQuad, NewPairQuad)
15:        break
16:      end if
17:    end if

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18:   end for
19: end if
20: end for
21: FINDINTERNALBOWTIES(BowTieMesh, QuadMesh, StartingQuad)
22: for each quad  $Q \in$  QuadMesh do
23:   if ! $Q.IsInternalMatched$  and  $Q$  does not have any internal matched neighbor then
24:     NewStartingQuad =  $Q$ 
25:     FINDINTERNALBOWTIES(BowTieMesh, QuadMesh, NewStartingQuad)
26:   end if
27: end for
28: return BowTieMesh

```

In addition to the extraction of the auxetic patterns from the input mesh, we also have the capability to create a flat plane mesh consisting of auxetic patterns (see Figures 6 and 7), which we then fabricate and wrap around a complex physical model (please see video). We prefer this approach over directly printing the 3D auxetic patterns since there is no need to use support structures to fabricate such flat models. In addition, printing times of these patterns are considerably less due to the fewer number of layers.

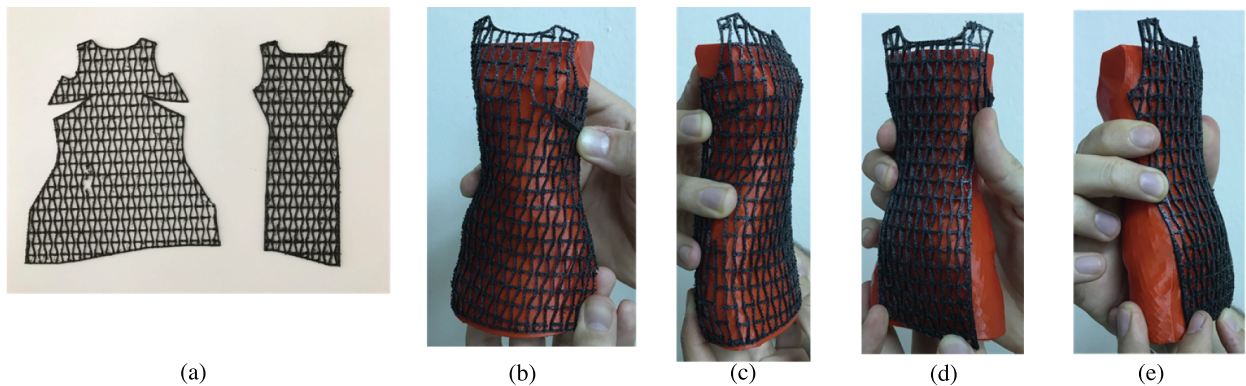


Figure 6. (a) 3D printed front and back parts of a dress; (b), (c) wrapping the front part and (d), (e) wrapping the back part. Please see video for further results.

3.3. Preparing extracted auxetic patterns for 3D printing

We show in Figure 8a a quad mesh of a Goblet model, which is the input of our auxetic pattern extraction algorithm described in Section 3.2. The output is the hexagonal mesh that we call the bow tie mesh (Figure 8b). Note that in the bow tie mesh, quads of the original mesh are turned into hexagonal bow ties.

After auxetic patterns are extracted, faces must be removed and remaining edges must be thickened for 3D printing. At this stage, we get help from Blender,¹ which is an open-source 3D graphics designing software. This software presents implementations that can be used for modifying meshes. We use Blender's wireframe and skin modifiers in order to get rid of the faces created by the bow ties and thicken the edges of the bow ties. The bow tie mesh in Figure 8b is processed in Blender and the desired print-ready structure is obtained. This structure constitutes auxetic reentrant honeycomb patterns without faces and with thickened edges as shown in Figure 8c. The fabricated result is shown in Figure 8d.

¹Blender(2017). 3D Creation Software[online]. Website <https://www.blender.org> [accessed 500.000+ per month].

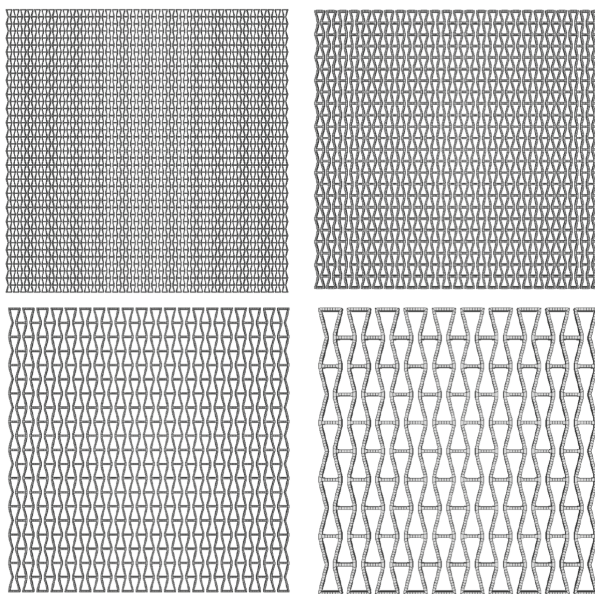


Figure 7. Auxetic planes consisting of differently sized auxetic patterns.

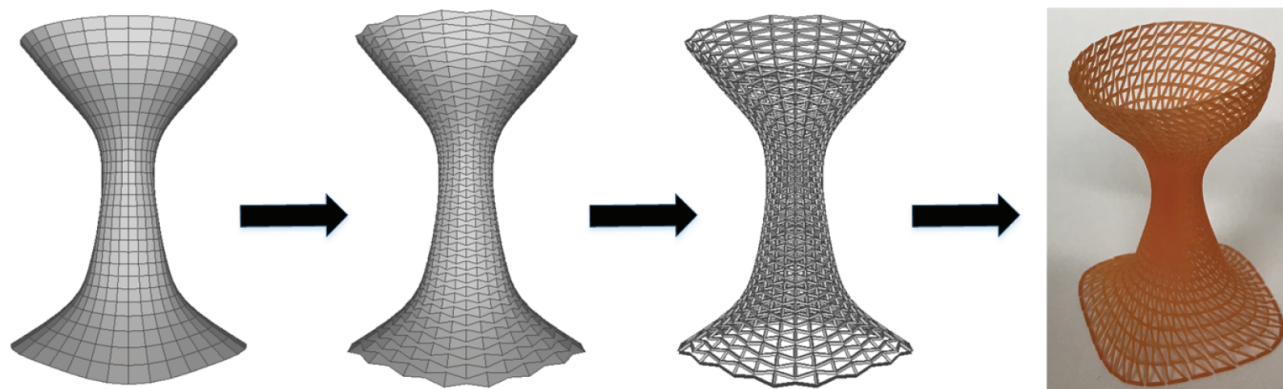


Figure 8. Our method remeshes the original design by extracting auxetic patterns. (a) Original design. (b) Auxetic patterns extracted from the original design. (c) Wireframe form of the extracted auxetic patterns. (d) Extracted auxetic patterns after fabrication.

4. Results and discussion

In this section of the paper, we evaluate the performance of the proposed method on various models and discuss the advantages and the limitations of the approach.

We applied our method to four different models, namely Goblet, Vase, Glove, and Spot. The results of the approach are provided along with original models in Figures 8, 9, 10, and 11. As can be seen from these figures, the desired auxetic patterns are properly obtained.

4.1. Advantages of extracting auxetic patterns for 3D printing

The estimated fabrication times and material consumptions using fused deposition modeling (FDM) technology for the models given in Figures 8, 9, 10, and 11 are summarized in Table 1. These numbers are all obtained

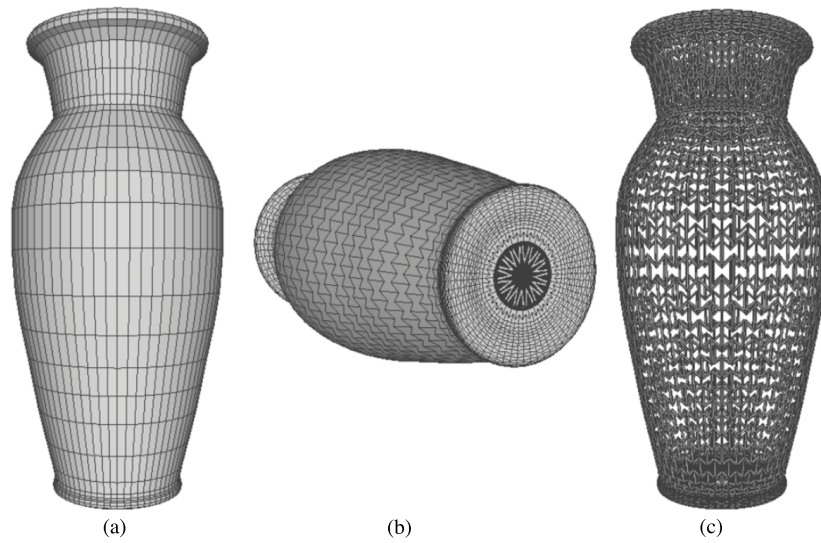


Figure 9. (a) Quad mesh vase. (b) Bow tie mesh vase. (c) Extracted auxetic patterns from vase prepared for 3D printing.

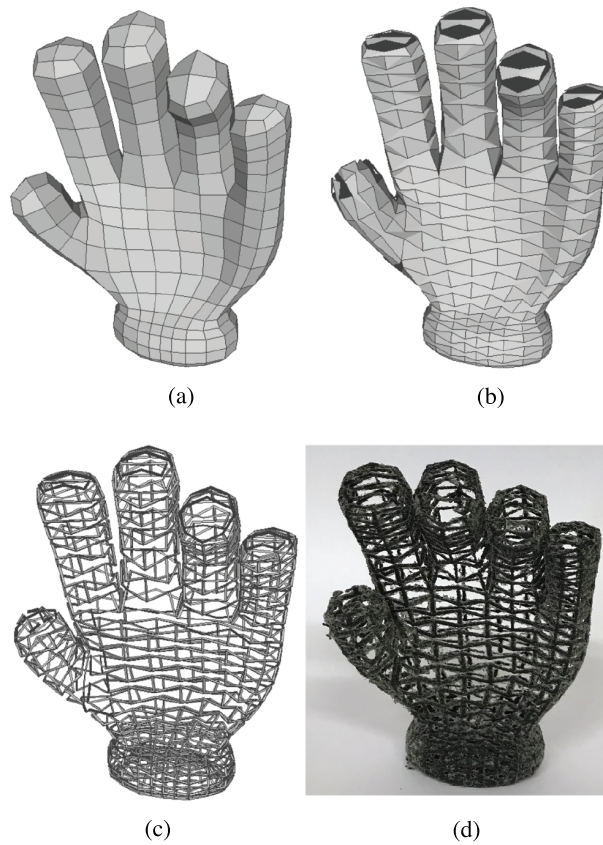


Figure 10. (a) Quad mesh glove. (b) Bow tie mesh glove. (c) Extracted auxetic patterns from glove prepared for 3D printing. (d) 3D printed glove.

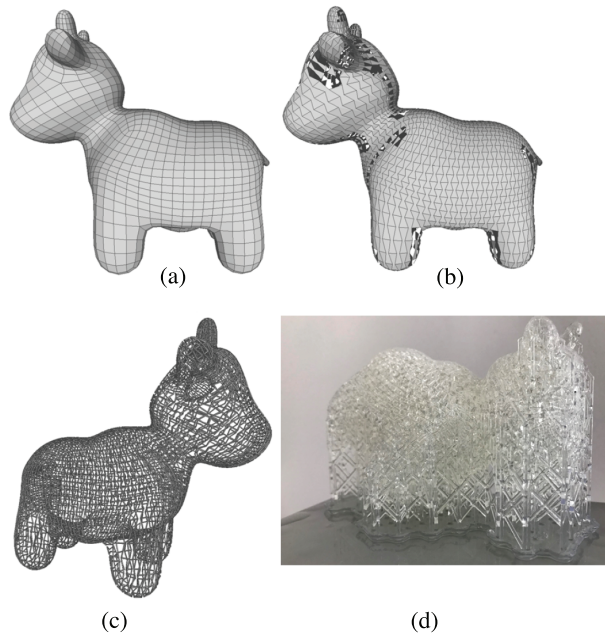


Figure 11. (a) Quad mesh spot. (b) Bow tie mesh spot. (c) Extracted auxetic patterns from spot prepared for 3D printing. (d) 3D printed spot.

from the 3D printing software Cura, available at the website of Ultimaker. In all these cases, the original models and the extracted auxetic patterns have the same dimensions. Identical fabrication parameters (material, nozzle diameter, layer height, print speed, etc.) are utilized for both the original models and the extracted auxetic patterns. Support structures are not generated and the infilling option is disabled in the 3D printing software for a fair comparison.

As can be inferred from Table 1, fabricating the extracted auxetic patterns reduces the time spent for 3D printing. Reduced fabrication time means that the 3D printer would work less and energy consumption would be reduced, resulting in a decrease in overall manufacturing cost. Additionally, printing the extracted auxetic patterns substantially reduces the material consumption, which constitutes the essential cost of 3D printing. Wang et al.[24] also pointed out that fabricating wireframe meshes of objects is a cost-effective method in the 3D printing world because of the low material consumption.

Table 1. 3D printing requirements of different models.

Target Model	Required time (min)	Required material (m/g)
Quad mesh goblet	372	3.05/24
Bow tie mesh goblet	156	0.63/4
Quad mesh vase	529	5.28/41
Bow tie mesh vase	303	0.66/5
Quad mesh glove	947	8.67/68
Bow tie mesh glove	360	1.05/8
Quad mesh spot	437	4.71/37
Bow tie mesh spot	195	0.71/5.33

Another benefit of the reduced fabrication time is that digital designs can quickly be validated. Wireframe bow tie meshes geometrically approximate the original meshes. In other words, wireframe bow ties replace the surface of the original meshes. 3D printing of the wireframe bow tie meshes requires less time, which lets designers quickly review their designs' appearances. Mueller et al. [26] also emphasized the importance of fast prototyping for designers.

4.2. Limitations

The major limitation of the proposed method is related to the fabrication step. Regardless of the selected additive manufacturing methodology, it requires special attention to manufacture these intricate patterns. In the earlier stages of our study, we were using the digital light processing (DLP) type of 3D printers to fabricate the artifacts. An example of these efforts is given in Figure 8 on the right. Since DLP printers are suitable for small and intricate parts, we managed to fabricate a goblet with a height of about 3 cm. When the size of the same part is increased, it becomes difficult to manufacture it properly due to the longer horizontal edges requiring support structures.

Due to the mechanical problems we had with the DLP printer, we switched to using the FDM type of printers, which have more limitations compared to DLP technology. It is not possible to fabricate small parts and complicated features, so we increased the size of the artifacts before printing them. As in the case of Figure 10d, we utilized support structures made of water-soluble material (PVA) to ease the fabrication. Furthermore, we generated flat auxetic patterns to decrease the fabrication time and material consumption. We realized this latest approach on a dress [29], whose details are provided in Figure 6 and in the accompanying video. In future studies, we plan to improve our assembling methodologies with the help of mechanical joints.

Lastly, we used stereolithography (SLA) to fabricate Spot (Figure 11d). Due to the density of the pattern, numerous support structures were generated and cured. Although it was manufactured properly, it is difficult to remove these support structures without damaging the surface. Therefore, we suggest using FDM technology with PVA support material for such intricate parts.

4.3. Performance

The algorithm was run on four different inputs with different sizes and shapes as shown in Figures 8 - left (goblet), 9a (vase), 10a (glove), and 11a (Spot). The numbers for the quad meshes and the running processes are exhibited in Table 2.

Table 2. Results of running auxetic patterns extraction algorithm for different inputs

Target model	# of quads	# of paired quads	# of internally paired quads	Running time (s)
Goblet	896	896	896	2.1
Vase	2784	2784	2752	7.1
Glove	536	536	504	1.5
Spot	2928	2818	2190	6.2

The first model, Goblet, is highly suitable for the algorithm. All bow ties are obtained from the quads. There are no gaps on the surface as shown in Figure 8 - middle left. The rest of the models, vase, glove, and Spot, are almost suitable for the algorithm. All bow ties are again found from the quads. However, some internal bow ties cannot be obtained due to the shapes of these models. There are some gaps on their surfaces as shown in Figures 9b, 10b, and 11b.

There are also models that are not very suitable for the algorithm. In Figure 12a, a famous model in the computer graphics world is shown, the Stanford bunny. Although the Stanford bunny quad mesh model was regularized by Peng et al. [30], it still contains irregular vertices. We tried our algorithm on this quad mesh. The numbers for the quad mesh and the running process are presented in Table 3. Additionally, the result of the algorithm can be seen in Figure 12b. There are some lanes consisting of gaps and interlaced bow ties as shown in Figures 12c and 12d. The algorithm needs to be improved for such intricate cases.

Table 3. Results of running auxetic patterns extraction algorithm for Stanford bunny model

Target model	# of auads	# of paired quads	# of internally paired quads	Running time (s)
Bunny	12087	11856	11004	351.6

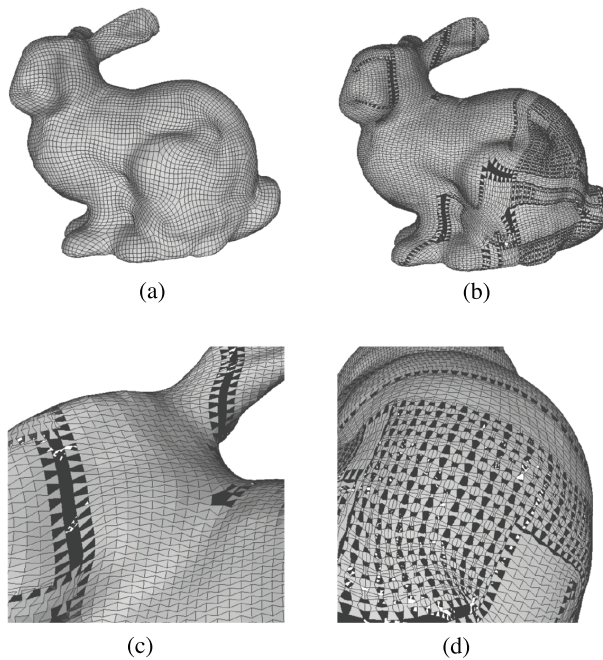


Figure 12. (a) Quad mesh Stanford bunny model. (b) Final result obtained by the algorithm. Zoomed to the lanes (c) consisting of gaps and (d) interlaced bow ties.

The algorithm was run multiple times for each quad mesh on an ordinary computer having 8 GB RAM and 2.40 GHz processor. The average of the running times was calculated and presented as the running time of the algorithm. The differences in running times of the algorithm for different quad meshes are as expected. An increase in the number of quads in the mesh increases the running time of the algorithm.

5. Conclusion

We developed a novel method for extracting auxetic patterns from 3D printable digital designs by modifying the existing mesh primitives directly and fully automatically. To this end, we presented a remeshing algorithm to convert a quad or triangle mesh into a hexagon mesh where each hexagon is bow tie shaped so the planar tiling of such bow tie hexagons exhibits auxetic material properties. The edges of the hexagon mesh were then inflated and printed with FDM, SLA, or DLP printers.

We fabricated our test models and observed the auxetic behaviors on the outputs. During the 3D printing processes, we encountered problems caused by the difficulties of fabricating these intricate patterns. We tried different methods to fabricate auxetic patterns and created objects consisting of auxetic patterns.

In future works, we plan to improve our algorithm in order to extract auxetic patterns from more complicated digital models. This may benefit from a multiresolution approach that employs auxetic patterns of varying sizes on the same mesh (Figure 7). Establishing smooth transition between such multiresolution patterns is expected to alleviate the gapping and interlacing problems demonstrated in Figure 12b. Such an approach will also enable varying the elasticity over the fabricated object, where the places tiled with smaller patterns will be less elastic than the ones tiled with larger patterns. Finally, we plan to fabricate using more functional 3D printers than the ones we employed.

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References

- [1] Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y et al. The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design* 2015; 69: 65–89.
- [2] Ma C, Wei LY, Tong X. Discrete element textures. *ACM Transactions on Graphics* 2011; 30 (4): 62.
- [3] Praun E, Finkelstein A, Hoppe H. Lapped textures. In: *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*; New Orleans, LA, USA; 2000. pp. 465–470.
- [4] Lefebvre S, Hoppe H. Appearance-space texture synthesis. *ACM Transactions on Graphics* 2006; 25 (3): 541–548.
- [5] Zhou K, Huang X, Wang X, Tong Y, Desbrun M et al. Mesh quilting for geometric texture synthesis. *ACM Transactions on Graphics* 2006; 25 (3): 690–697.
- [6] Garg A, Sageman-Furnas AO, Deng B, Yue Y, Grinspun E et al. Wire mesh design. *ACM Transactions on Graphics* 2014; 33 (4): 66–1.
- [7] Torres C, Campbell T, Kumar N, Paulos E. Hapticprint: Designing feel aesthetics for digital fabrication. In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*; Charlotte, NC, USA; 2015. pp. 583–591.
- [8] Dumas J, Lu A, Lefebvre S, Wu J, Dick C. By-example synthesis of structurally sound patterns. *ACM Transactions on Graphics* 2015; 34 (4): 137.
- [9] Chen W, Zhang X, Xin S, Xia Y, Lefebvre S et al. Synthesis of filigrees for digital fabrication. *ACM Transactions on Graphics* 2016; 35 (4): 98.
- [10] Schumacher C, Thomaszewski B, Gross M. Stenciling: Designing structurally-sound surfaces with decorative patterns. In: Benes B, Chen M (editors). *Computer Graphics Forum*. Volume 35. New York, NY, USA: The Eurographics Association and John Wiley & Sons Ltd, 2016, pp. 101–110.
- [11] Zehnder J, Coros S, Thomaszewski B. Designing structurally-sound ornamental curve networks. *ACM Transactions on Graphics* 2016; 35 (4): 99.
- [12] Zhao H, Gu F, Huang QX, Garcia J, Chen Y et al. Connected fermat spirals for layered fabrication. *ACM Transactions on Graphics* 2016; 35 (4): 100.
- [13] Jacobson A, Baran I, Kavan L, Popović J, Sorkine O. Fast automatic skinning transformations. *ACM Transactions on Graphics* 2011; 31 (4): 77.

- [14] Sahillioglu Y, Yemez Y. Minimum-distortion isometric shape correspondence using EM algorithm. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 2012; 34 (11): 2203–2215.
- [15] Spillmann J, Teschner M. Cosserat nets. *IEEE Transactions on Visualization and Computer Graphics* 2009; 15 (2): 325–338.
- [16] Wolff K, Poranne R, Glauser O, Sorkine-Hornung O. Packable springs. *Computer Graphics Forum* 2018; 37 (2): 251–262.
- [17] Perez J, Thomaszewski B, Coros S, Bickel B, Canabal JA et al. Design and fabrication of flexible rod meshes. *ACM Transactions on Graphics* 2015; 34 (4): 138.
- [18] Panetta J, Zhou Q, Malomo L, Pietroni N, Cignoni P et al. Elastic textures for additive fabrication. *ACM Transactions on Graphics* 2015; 34 (4): 135.
- [19] Schumacher C, Bickel B, Rys J, Marschner S, Daraio C et al. Microstructures to control elasticity in 3d printing. *ACM Transactions on Graphics* 2015; 34 (4): 136.
- [20] Martinez J, Dumas J, Lefebvre S. Procedural Voronoi foams for additive manufacturing. *ACM Transactions on Graphics* 2016; 35 (4): 44.
- [21] Konakovic M, Crane K, Deng B, Bouaziz S, Piker D et al. Beyond developable: computational design and fabrication with auxetic materials. *ACM Transactions on Graphics* 2016; 35 (4): 89.
- [22] Guseinov R, Miguel E, Bickel B. Curveups: shaping objects from flat plates with tension-actuated curvature. *ACM Transactions on Graphics* 2017; 36 (4): 64.
- [23] Schumacher C, Marschner S, Cross M, Thomaszewski B. Mechanical characterization of structured sheet materials. *ACM Transactions on Graphics* 2018; 37 (4): 148.
- [24] Wang W, Wang TY, Yang Z, Liu L, Tong X et al. Cost-effective printing of 3d objects with skin-frame structures. *ACM Transactions on Graphics* 2013; 32 (6): 177.
- [25] Lu L, Sharf A, Zhao H, Wei Y, Fan Q et al. Build-to-last: strength to weight 3d printed objects. *ACM Transactions on Graphics* 2014; 33 (4): 97.
- [26] Mueller S, Im S, Gurevich S, Teibrich A, Pfisterer L et al. Wireprint: 3d printed previews for fast prototyping. In: *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*; Honolulu, HI, USA; 2014. pp. 273–280.
- [27] Peng H, Wu R, Marschner S, Guimbretiere F. On-the-fly print: incremental printing while modelling. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*; San Jose, CA, USA; 2016. pp. 887–896.
- [28] Wu R, Peng H, Guimbretiere F, Marschner S. Printing arbitrary meshes with a 5 dof wireframe printer. *ACM Transactions on Graphics* 2016; 35 (4): 101.
- [29] Narain R, Samii A, O’Brien JF. Adaptive anisotropic remeshing for cloth simulation. *ACM Transactions on Graphics* 2012; 31 (6): 152.
- [30] Peng CH, Zhang E, Kobayashi Y, Wonka P. Connectivity editing for quadrilateral meshes. *ACM Transactions on Graphics* 2011; 30 (6): 141.