MECHANICAL METAMATERIAL CONTINUUM MATERIALS REALIZED THROUGH 3D PRINTING USING COMPLIANT MECHANISMS TECHNIQUES

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ABSTRACT

Recently developed classes of mechanical metamaterials that couple twisting with linear and volumetric expansion show great promise for the fields of soft robotics, deployable structures, and medical devices. These twisting auxetics can convert torque from conventional motors directly into expansion. Previously they have been realized only as assembled units, but in order to be usable in metamaterial structures they must be fabricable as a single continuum of material. However, the complex joints and relations between layers of material are not compatible with conventional fabrication processes. We use mono-material 3D printing of compliant materials and compliant mechanism design techniques to produce 3D printable continuum material versions of these twisting metamaterials. We show that we can produce continuum analogs of rotating bilayer joints, angle preserving joints, and multi-component joints and replicate the bilayer polyhedral auxetics. We show how these techniques can be used to fabricate planar structures that can be folded into 3D objects. These printing and design techniques allow for the easy and scalable fabrication of twisting auxetic metamaterials which can be actuated with motors.

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1. INTRODUCTION

Volumetric expansion is used in many biological and soft robotic systems for movement. Soft robots often use fluid flow or thermal phase changes to drive expansion [14, 15, 16, 17]. While they have been useful for some limited grasping and movement tasks, thermal actuation is slow and pneumatic actuation is susceptible to leaks and punctures and is inefficient. Auxetic metamaterials are characterized by negative Poisson's ratio, causing them to expand under strain. These materials can be planar arrays of two-dimensional [18, 11, 13] or three-dimensional cells [8, 2, 7]. The Poisson's ratio and directional anisotropy of these materials are geometrically determined by the metamaterial structure and its underlying symmetries. The structure is scale and material agnostic, making these metamaterials widely applicable. The nature of the joints determines the scale of the meta-material cell. Three-dimensional auxetics that can be twist driven can be the basis for volumetric expanding robots powered by motors.

It was shown in [6] that bilayer cellular auxetic structures with polyhedral symmetries are ideally suited for motor-driven volumetric expansion. However, the work relied on

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discrete structures that have a high assembly cost. Bilayer auxetics consist of placing a mirror copy of a layer on top of another and aligning common points of rotation. Producing bilayer auxetics out of a continuum of material requires alignment preserving joints not previously deployed in continuum auxetic models.

Here we show how we can use compliant mechanism techniques and additive manufacturing to create compliant bilayer auxetic cells. These cells expand and contract volumetrically when antipodal points are twisted. We employ living hinge-based designs which approximate rigid links connected by pin joints. We use compliant mechanism design techniques [1, 5] to produce continuous material auxetic linkages a library of joint designs needed for these structures. We then use these techniques to produce a three-dimensional platonic auxetic unit cell.

In order to reduce the cost and time of production, the parts are designed to be printable with desktop fused filament fabrication (FFF) and require no support material, reducing post-processing time. To accomplish this, we fabricate 3D polyhedral auxetic cells from planar prints based on the 2D nets of the 3D polyhedral auxetic cell. Making net models that can be auxetic structures required us to develop a modified living hinge geometry

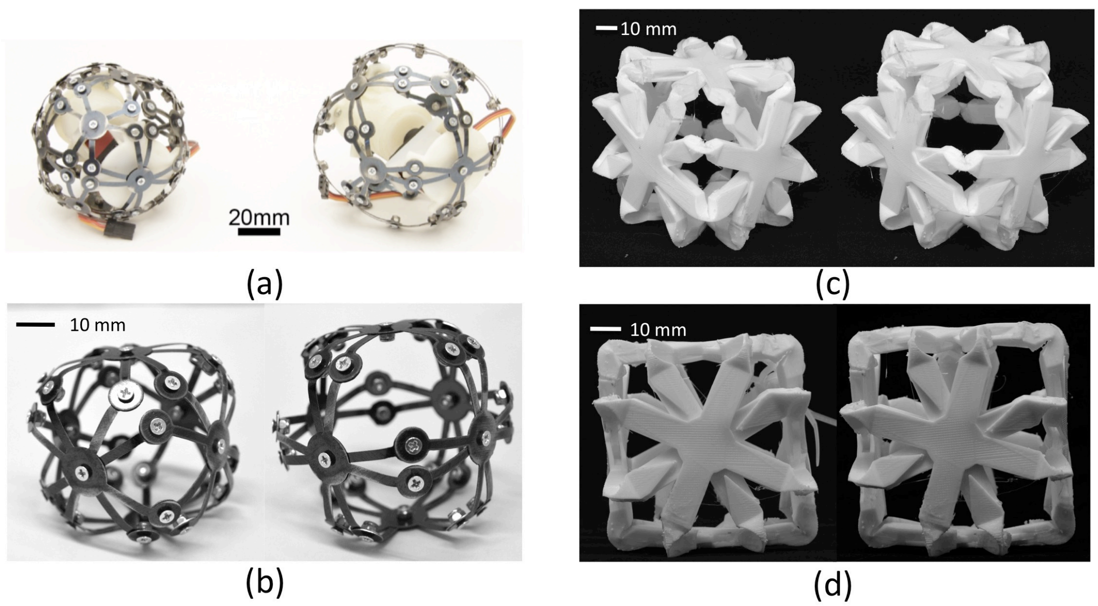

Figure 1: Bilayer auxetics can be used as motor driven actuators(a). Polyhedral bilayers can be fabricated from discrete components (b) or 3D printed as a continuous piece of material and assembled into an auxetic structure (c, d) .

that both enforces the design rules for support free FFF and allowed for significant defomation of the joint along one axis, while acting as a single degree of freedom hinge in another.

In this paper we:

- Develop the planar joints needed to replicate bilayer planar auxetic structures

- Show how to extend this method to produce 3D polyhedral auxetics using net based designs
- Demonstrate that these designs can be fabricated on low cost FFF printers without support material.

2. BACKGROUND

2.1 Compliance in Auxetics

Most auxetic cellular materials can be modeled as repeating arrays of linkages. These linkages form a single degree of freendom network between cells causes the material to expand and contract as a whole. Planar auxetic patterns include re-entrant honeycomb and arrows, chiral missing-rib cells, and corner-connected rotating polygons, all of which are modeled as rigid links or polygons connected by pin joints. With the right choice of internal pattern these lattices can obtain up to Poisson's ratio of -1 [23].

Compliant versions of these use either living hinges or bending of the links as the main mode of deformation [12]. The living hinge technique has been applied to several single layer 3D auxetics. Buckliballs, for instance, use cutout circles in a spherical surface to create a pattern of polygonal faces connected by simple joints, which rotate into their collapsed state when their interconnecting members buckle [9]. Through special geometry, all of the connections undergo the same buckling mode, keeping the collapse of the sphere radially uniform. These compliant spheres were possible to cast from a single material due to their geometric simplicity.

2.2 Compliant Mechanism approaches to complex joints

It is possible to convert pin joint models to continuous materials because of compliant mechanisms. A lumped-compliant system – one in which compliance is mostly localized at small-length joints rather than distributed over a larger flexing area – corresponds to a linkage mechanism with rigid links joined by hinges with specific degrees of freedom [5, 1, 19]. These consist of a combination of simple living hinges between thicker approximately rigid beams.

More complex joints can be constructed by joining simple elements into serial configurations. For example, when creating a compliant version of a known mechanism such as the Peaucellier–Lipkin linkage which requires more than two links to come together at a single point, these points are decomposed into two slightly offset simple living hinges [21]. This allows the compliant version to be made from simple joints. By taking advantage of the flexibility of additive manufacturing, we do not have this constraint, freeing us to making joints such as those in the following section that are not internally planar.

2.3 Actuation of Auxetics

There have been several approaches to actuate auxetic structures. Buckliballs use pneumatic evacuation of hollow spheres to drive twisting volumetric collapse [9]. This rely on having a closed evacuable chamber in the center of the sphere, creating a uniform inward pressure. As with most soft robotics actuation techniques, this mean combining the cells expands the number of failure points in the system, as a single puncture could prevent all connected cells from actuating. Other approaches have relied on thermally actuated shape memory alloys and polymers to expand or contract the structure. Like other thermal actuation methods, this makes for a slow actuation that is power intensive [26].

Handed shearing auxetic cylinders introduced twist-based expansion and contraction without pneumatic actuation [3]. These cylinders extend and shrink with motor-driven rotation. This motion is coupled with some radial expansion of the cylinder. While primarily employed as cylinders, the same principles were compatible with spherical structures. In [6] the concept was extended to show that twist based actuation could generate volumetric expansion by generating torques between antipodal points on a structure.

3. JOINTS FOR COMPLIANT AUXETICS

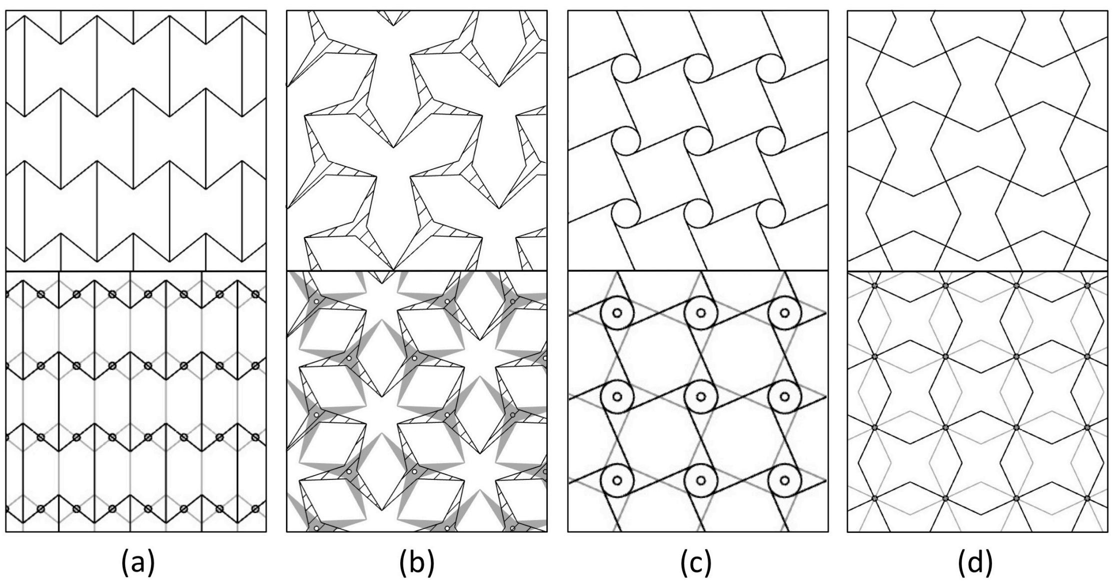

Figure 2: Bilayer planar auxetic cellular patterns require joints connecting different numbers of elements. From left: (a) re-entrant honeycomb, single and bilayer (b) rotating triangles, which requires three segments per layer connected at the rotating center (c) and (d) chiral and missing rib, which require four segments connected at the rotating center.

There are a wide variety of known auxetic patterns, both planar and three-dimensional. All planar auxetic patterns have a bilayer counterpart connected between the layers at the points of rotation [8, 27]. Figure 2 shows some of the canonical planar auxetic patterns and their bilayer counterparts. Figure 2 c. shows the chiral bilayer auxetic described in [8] and figure 2 d. shows the auxetic described in [27]. The other bilayer auxetics are designed by analogy. For each bilayer there is an inter-layer joint at the point where the structures remain fixed relative to one another.

Bilayer planar structures are mirrored between horizontal layers, leading to mirrored rotational movement. The inter-layer joints thus need to have a single rotational degree of freedom. The bilayer chiral cells in f. are designed in [8] with a rotating joint consisting of angled beams connecting the layers. This joint adds an auxetic element in the third axis, but it constrains the direction of movement and in a volumetric cell would add unnecessary internal stress. We sought a design which could eliminate this extra movement and keep the layers a fixed distance apart while still maintaining auxetic behavior in plane.

These joints are determined by the number of segments that meet at the central point on each layer, forming a rigid body. In the re-entrant honeycomb pattern, these cross-layer joints consist of two simple crossed beams. For the rotating triangle pattern, each layer has three segments meeting at the central rotating point. The chiral pattern and the missing rib pattern each have four segments per layer meeting at the inter-layer joint.

3.1 Bilayer movement

The bilayer structures have a complex joint at their cross-layer bonds. For the simplest of these joints – two beams crossing at a point – a flexure joint consisting of a square of four simple flexures at the corners of four beams (a structure named the Q-joint in [1]) provides a planar alternative with similar behavior. As the hinge flexes the links stay approximately parallel but they are only colinear at the center of the range of movement; at the maximal angles the beams are offset up to the link length of the internal tetrahedron. This behavior does not mimic the pin joint closely enough to be used in these auxetic parts, and does not work at all for the joints with more crossing beams.

Our solution is a bilayer joint inspired by flex bearings (figure 3 d.). Flexure joints between a connecting central core and a concentric surrounding free layer allow the two layer elements to rotate with respect to one another. Joints are characterized by the number of beams attached to the central point for each of the two layers.

Because beams move in the same plane rather than in two planes, the width of the beams presents a limit to the angle range of these joints. The two layers cannot cross over one another and are constrained by hitting their neighboring beam. Cutting an angle in the beams to create a narrower region near the center increases the angle range of movement but weakens the rigidity of the layer. This problem is more significant the larger the number of segments in the layer, as crowding of the center increases.

	2-segment	3-segment	4-segment
Ideal	180°	120°	90°
Assembled	122°	52°	39°
Printed	70°	54°	28°

Table 1: The angle ranges for the printed bilayer joints are somewhat lower or comparable to the assembly structures [6], although both are short of the ideal range.

As seen in table 1, the two-segment joint pictured in figure 3 a. has approximately 70 degrees of range, a loss over the assembled structure in [6]. The range of the three-segment joint in b. is approximately 54 degrees of range and the range of the foursegment joint in c. is 28 degrees. The angle range decreases with the crowding of neighboring segments around the central core. These angle ranges are sufficient to produce some auxetic behavior but do not match that of the spring steel assembled cells.

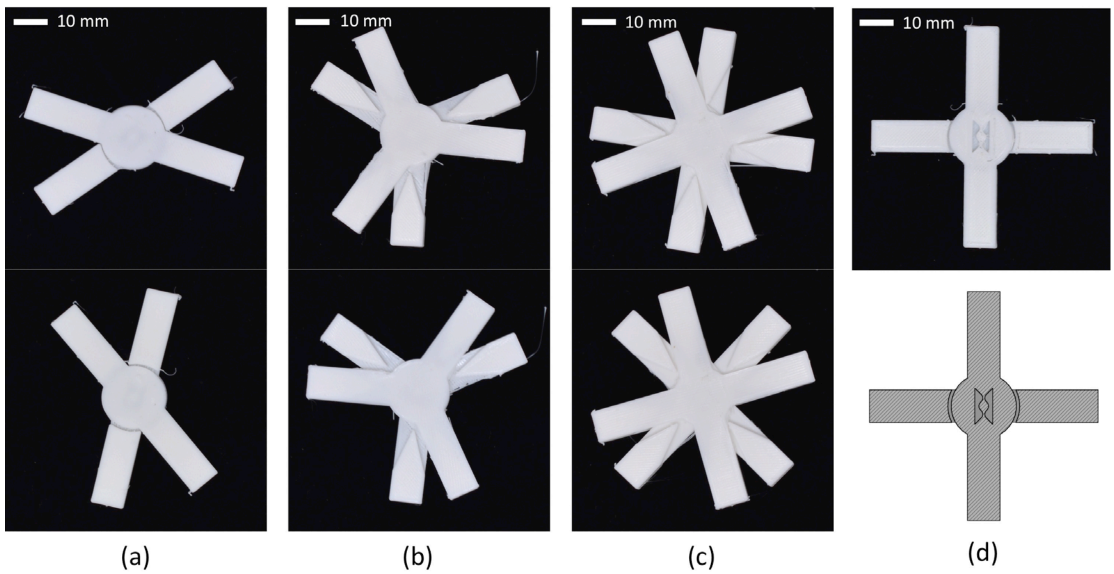

Figure 3: 3D printed TPU test parts of bilayer joints demonstrating range of motion. From left: (a) two segments per layer, (b) three segments, (c) four segments, (d) internal structure with living hinge attached to central core: 3D printed test part and CAD model.

4. EXTENDING TO THREE DIMENSIONS

4.1 Using Nets to Print Polyhedral Auxetic Cells

Producing bilayer polyhedra from the compliant bilayers developed in section 3 can be done in several ways. Firstly, complaint faces could be fabricated as individual sections and then bonded together. Secondly, the faces could be rotated and aligned in CAD, joined with a simple joint, and printed as a single piece. Finally, the system could be printed as a planar net, folded, and assembled.

All polyhedra can be segmented into a planar structure by selective cutting and flattening of edges to form a net. For each polyhedron, there are families of nets in which the polygonal sides are unfolded into non-overlapping planar connected figures. Figure 4 row 2 shows example nets for several polyhedra along with models of bilayer auxetics. Compared to assembling the cells or printing the individual faces separately these nets significantly reduce both the number of seams and the number of prints required to manufacture these polyhedral cells.

Compared with printing as a single unified part, the net method also significantly reduces the need for support material, and with it the need for significant post processing. If the structures from section 3 were applied to the patterns in figure 5 and printed, there would be a large internal void in each model. This void would need to be filled with a support structure to facilitate printing the top faces. While some processes such as selective laser sintering use the unused powder as support and thus do not require support structures, most processes require an additional printed support structure that needs post processing to remove and takes extra time to print.

We chose to use FFF fabrication as described in section 5 because it is widely accessible and cheap to use. FFF in particular requires the use of support material to fill the voids that direct fabrication would produce. On a mono-material FFF system, the support material is the build material, making the process of support removal a time consuming manual process. By eliminating the need for support material, we can use the cheapest and most widelyt available 3D printing method. In exchange we retain the post processing requirement of manually folding the edges and bonding the faces together. To use printed nets we need a joint which can both connect printed faces and be folded, and a joint that can be bonded after fabrication.

4.2 Net joints and bonds.

A joint in our net exists at the vertex of our polygons. It must constrain the length of the joint while allowing for bending along the edge of the net, and must be able to change angle as it moves along the edge of the net. This constrains us to using a version of a universal joint with two degrees of freedom. Previous polyhedral structures were based on circular notch living hinges or bending beams. Circular notches are effective at creating a single degree of freedom joint but are not suitable for being folded along the net. A bending beam structure would be a three degree of freedom joint, while the joints along the edges of the net need to have two degrees of freedom. As a result we are forced to use a different style of joint from other 2D and 3D auxetic structures.

While there are several compliant joints equivalent to universal joints, we chose to modify the circular notch style to allow for the bend. This modification allowed us to enforce the 45 degree angle restriction on overhangs commonly used in monomaterial 3D printing. As seen in figure 5B, we also extended the hinge upwards out of plane in an arc to better resist parasitic twisting. This constrains most of the movement to the bending mode that keeps the beams in plane with the faces of the polyhedron.

Nets place cuts along the edges of the polyhedral structure. Applying this to an auxetic structure would put the cut directly through a hinge, which is not an ideal place for bonding. As a result we moved the location of the cuts. The part was designed with seams within the beams and away from the hinges, reducing the stress on the seam. The seams could then be joined with thermoplastic adhesive and had significantly more surface area for bonding. The printing and bonding methods are discussed in the next section. As seen in Figure 1, the combination of cut structure, bilayer joint, edge joint geometry, and bonding methods allowed us to take a net and form a bilayer polyhedral auxetic.

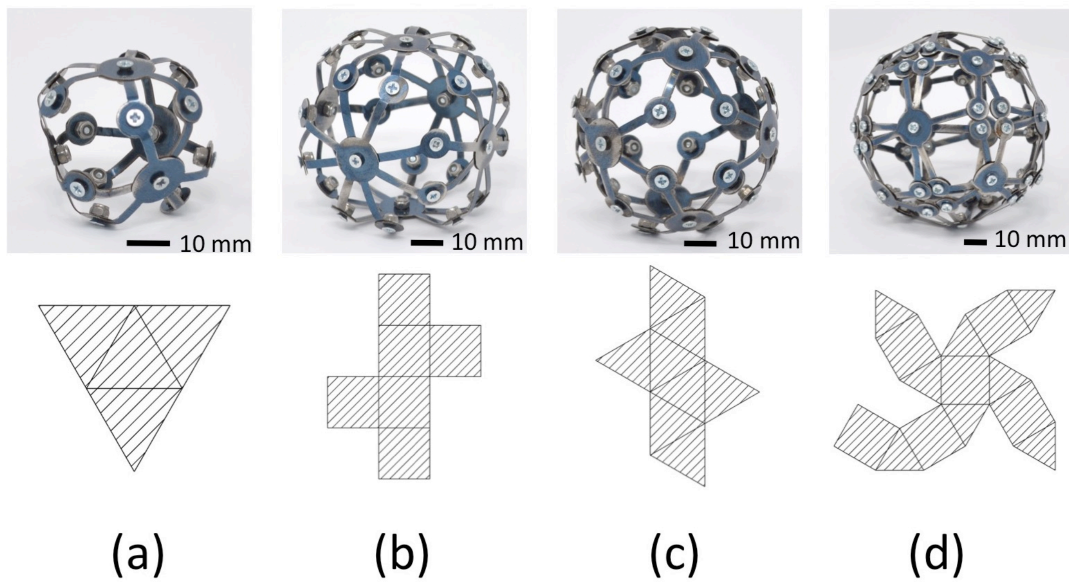

Figure 4: The polyhedral auxetic cells from [6], created by tiling a jointed pattern on the faces of polyhedra. From left, the cells are based on the rotating tetrahedron (a), cube (b), octahedron (c), and cuboctahedron (d). These cells can be made as a single layer (top) or bilayer (middle) and each polyhedron can be unfolded into a non-unique net (bottom).

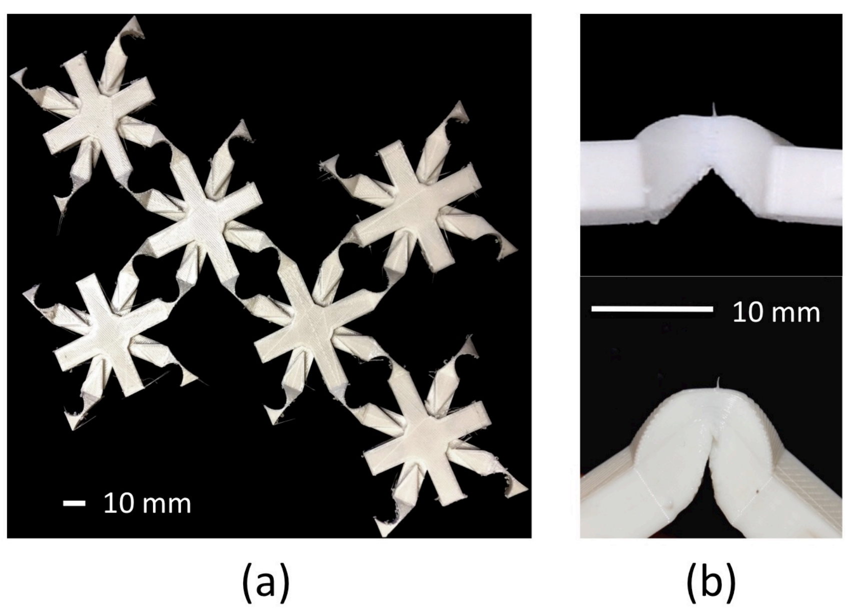

Figure 4: The print on a cubic net (a, background digitally removed) has joints placed on the folding edges between the square faces of the assembled cube. The joint at the edge (b) is notched in order to fold over the edge when the net is assembled.

5. PRINTING AND BONDING METHODS

We fabricated the final part in TPU (NinjaTek Cheetah in Snow) on a desktop FFF printer (Creality Ender 3 Pro). Extrusion was raised to 105% to maintain solidity and infill 100% using a concentric pattern, keeping the print lines aligned along the joints. Planar printing avoids issues of print anisotropy in the hinges. Layer thickness was .2 mm. For the regions requiring layers to remain separate, internal to the bilayer joints, a gap of two layers (.4 mm) was built into the part. This allows the lower printed layer to cool, making the inter-layer adhesion very weak. These layers can then be easily separated in the finished print. We printed the three-dimensional cell shown in figure 1 as a planar part, unfolded using the net in figure 4 j. We used thermoplastic adhesive to bond the net together.

6. CONCLUSIONS AND FUTURE WORK

We introduced a series of compliant joints used to replicate bilayer auxetic structures as continuous material complaint mechanisms. We then used these joints to replicate a bilayer polyhedral auxetic cell. These polyhedral auxetic cells can be fabricated in planar form using a commercial desktop mono-material FFF printer. We conclude that using net-based construction, these three-dimensional metamaterial cells can be manufactured with limited manual post processing and in a cheap and accessible manner. This process considerably reduces the assembly costs from the spring steel assemblies.

In making these compliant mechanisms we have sacrificed the material-agnostic nature of the auxetic metamaterial design. The geometric parameters of these hinges are designed for FFF printed TPU, which limits the range of compliance and the detail present in the parts. With other manufacturing processes it will be possible to create better detail and smaller or larger parts, but these designs will have to be reworked to suit other materials and processes. This will require using more expensive and less accessible processes such as CLIP, SLS, and HP Jet fusion.

We believe this work represents a significant step towards producing large arrays of auxetic cells whose expansion can be driven by motors. This will provide a more robust and controllable form of volumetric actuation for soft robots when compared to pneumatics and a faster and more controllable method than thermal driven processes.

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