Midterm report: Analysis of 3D-Printed Auxetic Lattice Structures for Robotic Skin Applications

Beom Jun Kim[1] and John Meshinsky[1]

***Abstract*— This report evaluates the suitability of auxetic structures for robotic skin by leveraging their negative Poisson ratio, which provides a combination of energy absorption, low stiffness, and flexibility suitable for protective applications.[1][2][3] The project compares different auxetic lattice designs by assessing deformation behavior, shock absorption, and structural stability. The focus of this project is to simulate and test the mechanical behavior of auxetic lattice structures for potential use as robotic skin. Specifically, the system aims to measure Poisson's ratio, stiffness, and shock absorption capabilities of various 2D lattice structures manufactured from thermoplastic polyurethane(TPU). TPU's high elasticity and manufacturability make it an effective material for these simulations.[4][5] The lattice is modeled as a network of nodal-spring beams. This representation naturally produces the expected negative Poisson's ratio[6]; however, the structure tends to collapse or fold in on itself at higher deformations. This suggests that the current model lacks sufficient constraints and mechanical realism. Improving stability and preventing collapse are central goals before progressing to systematic testing.**

I. Background and Related Work

Auxetic materials with a negative Poisson's ratio have been studied extensively for energy absorption, indentation resistance, and vibration damping in foam and composite structures [1][2][3][8]. 3D-printed TPU lattice architectures, in particular, enable tunable stiffness and deformation behavior through control of unit-cell topology, printing parameters, and geometric complexity [4][5][7]. Building on these results, our work focuses on beam-based auxetic lattices modeled at the nodal level and evaluated numerically for their suitability as robotic skin.

II. Progress

1. Lattice Structure Creation

An initial function was developed to generate lattice geometries by creating nodes and defining connectivity patterns. This procedural generation makes it possible to construct multiple lattice types rapidly and consistently. The lattice is modeled as a network of nodal-spring beams, similar in spirit to beam-based auxetic foam models used in prior work.[7] After generating the base structure, cleanup functions refine the geometry—for example, by subdividing connections to approximate beams more realistically and merging overlapping nodes to maintain proper topology. These steps help ensure the lattice behaves more like a continuous material rather than scattered data points.

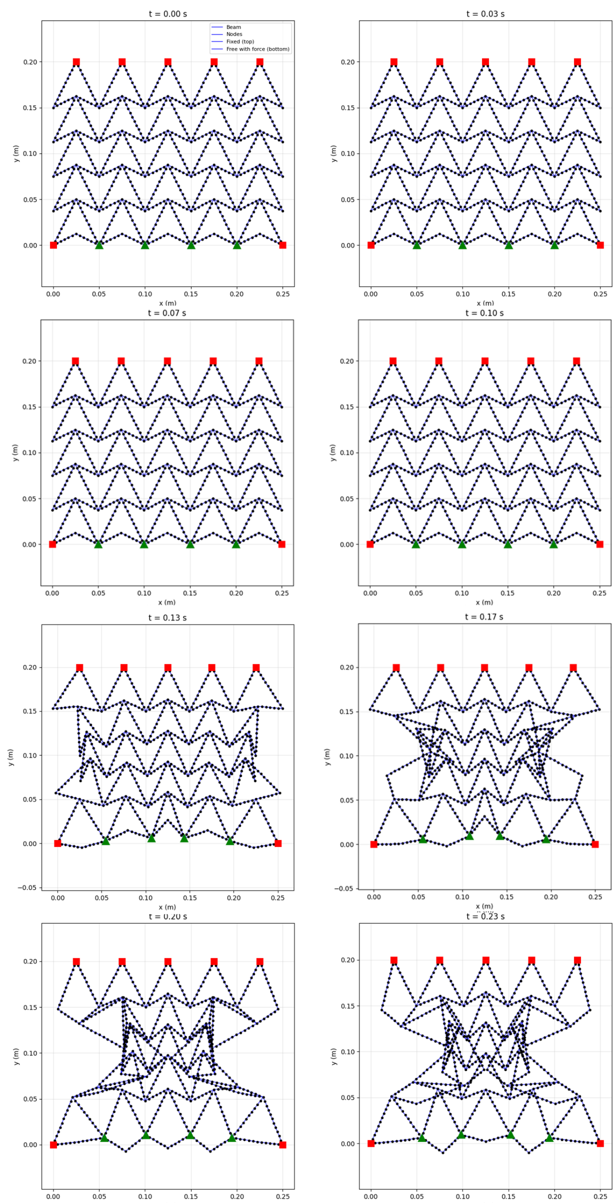

Fig. 1. Lattice creation and force application plot for t = 0.00, 0.03, 0.07, 0.10, 0.13, 0.17, 0.20, 0.23

[1]Authors are graduate student of Mechanical and Aerospace Engineering, University of California Los Angeles, 405 Hilgard Avenue, United States of America

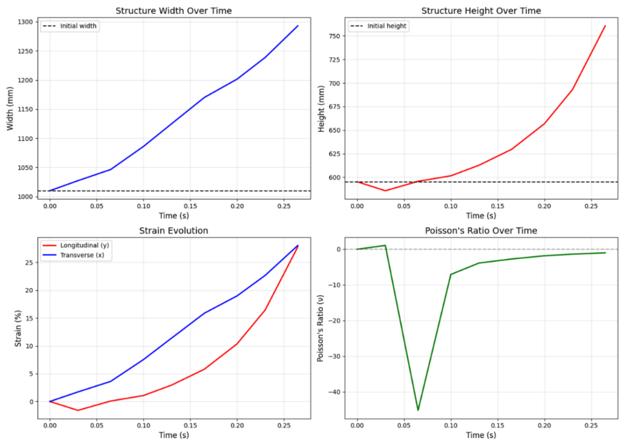

Fig. 2. Time evolution of structure dimensions, strain, and effective Poisson's ratio during actuation.

2. Application of the Load
The simulation applies forces and updates node positions over time using the Implicit Method. The forces considered include: bending (from angular deviation between connected beams), stretching (from beam elongation), inertial (from node movement), and externally applied compressive or tensile forces. Environmental forces such as gravity are excluded to isolate the intrinsic behavior of the auxetic pattern under controlled loading.

3. Measurement of Values
The simulation computes the Poisson ratio by dividing the average height deformation by the average width deformation using the extreme nodal positions.[7] Additional measurements compare the applied load with the resulting deformation, which allows the estimation of the stiffness and shock absorption properties.

III. Issues

A. Door Hinge Effect

The lattice tends to rotate around its vertices due to local compliance, effectively creating a hinge-like joint where multiple beams meet. Because these vertices experience several simultaneous force contributions, their motion becomes overly flexible, causing unintended rotational freedom. This reduces the fidelity of the simulation by allowing unrealistic deformation modes. Since the lattice is generated, the spacing of nodes or the lengths of the beams may not be uniform across the structure. When the nodes are unevenly spaced, parts of the lattice become more flexible or more rigid than intended, which can exaggerate the hinge effect or cause unexpected bending. Improving the structure generation so that node spacing is more consistent would help the lattice respond more predictably. Adjusting the cleanup function to regulate beam lengths and ensure that each section of the structure behaves similarly would make the deformation more uniform.

B. Nodal Overlap

A significant challenge is the overlap of nodes and beams, since nodes are modeled as non-physical points. This allows multiple nodes to occupy the same space, resulting in excessive force interactions and geometric collapse. As a result, the lattice can fold back on itself, producing unrealistic behavior that must be corrected for an accurate measurement.

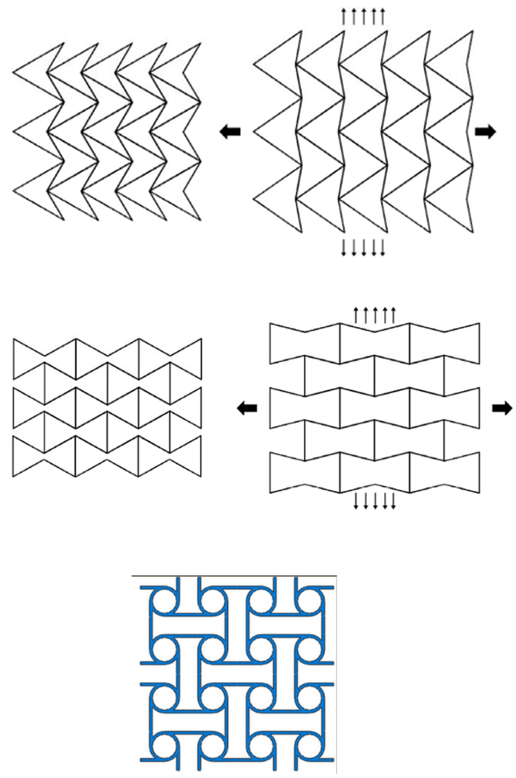

Fig. 3. Schematic of the three candidate auxetic lattice patterns investigated in this study.

C. Numerical Instability in the Simulation

It seems that numerical instability occurs when forces accumulate, especially with stiff joints or collision forces. This may cause the simulation to behave unpredictably, leading to vibration, overshoot, or collapse due to force miscalculation. To address this would be to adjust the simulation's time stepping. Smaller time steps, or more. A stable update method would allow the solver to better track the propagation of forces through the lattice. However, this would add to the runtime of the simulation. Adding gentle damping to the system could also help remove unwanted oscillations and allow the structure to settle more realistically.

D. Constraints and Fixed Boundaries

Another possible issue is that the lattice's boundaries may be too rigid or too loose. If the edges are fixed too strongly, the forces may build up along the boundary instead of being distributed through the lattice. If the boundaries are too free, the structure may slide or rotate in ways that do not represent realistic conditions. To fix this, the simulation could use supports that mimic physical clamps or mounting points. Instead of locking nodes entirely in place, the simulation could apply partial constraints that allow slight movement while still restricting unrealistic drifting.

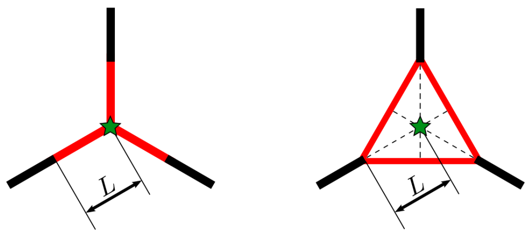

Fig. 4. Two types of joints, called Y-joints and 1-joints [13]

IV. Resolutions and Future Steps

A. Application of Stiff Joints

One possible strategy to address vertex compliance is to increase rotational stiffness at critical nodes. Some prior work on auxetic lattices uses stiffened joints to restrict rotation and enforce more realistic bending. This may improve structural behavior but could also introduce stiffness gradients, potentially reducing uniformity across the lattice. [1][7]

B. Applying Meshed Walls

Alternatively, using thicker, meshed wall elements rather than simple beams could better represent printed TPU structures. While this approach enhances geometric fidelity and reduces node overlap, it also increases computational demands due to the larger number of nodes and additional constraints.[4][5]

C. Collision Forces

Introducing repulsive or collision-based forces between nodes would help preserve physical constraints by preventing overlap. This requires detecting node pairs within a threshold distance and applying counteracting forces based on the predicted trajectory. Implementing this system would better simulate the physical behavior and hopefully reduce collapse experienced. While repulsive forces can prevent nodes from overlapping, they may not fully address situations where multiple beams move toward the same area. When the structure folds or twists, several nodes may approach each other quickly, and a simple repulsion force may not respond fast enough. A more effective approach would be to detect node pairs that are moving toward one another and apply preventative forces earlier in the simulation step. This would make the structure behave as if the beams had physical thickness instead of passing through each other.

D. Measuring Shock Absorption and Stiffness

Once stability issues are resolved, deformation data can be reliably analyzed. Differences between initial and final configurations under controlled loading will provide clear measures of stiffness and shock absorption. These metrics can then be compared across various lattice designs.[1][3][7]

E. Limitation of the current material model

In the present simulation, the TPU lattice is modeled as a linear elastic material with a constant Young's modulus E=26 MP, regardless of the strain level. However, experimental studies on thermoplastic polyurethanes report a strongly strain-dependent stiffness: once the axial strain exceeds the small-strain regime (on the order of a few to tens of percent), the tangent modulus increases and the material exhibits pronounced strain-stiffening behavior under compression and cyclic loading.[14] This non-linear stiffening is not captured in our current model, which likely contributes to the over-prediction of lateral deformation and under-prediction of the effective stiffness observed in the simulations compared to our physical tests. As a next step, we plan to incorporate a non-linear constitutive law for TPU — for example, a piecewise strain-dependent modulus ϵ or a calibrated hyper-elastic model — and update both the stretching (EA) and bending (EI) terms accordingly, so that the simulated lattice response under large compressive deformation better matches the measured behavior.

V. Change of Scope and Considerations

Testing the structures in 3D was initially considered, but time constraints and limited necessity for the current design goals make this out of scope. The 2D analysis already provides sufficient insight for the comparison of lattice architectures for robotic skin applications. Our main focus should simulating the lattice structures deformation to extract the values and measurements that we would need.

A. Sensitivity of Measurements

The current Poisson ratio and stiffness calculations depend heavily on the extreme node positions. If a small If the region of the lattice collapses or bends more than expected, the measurement may not represent the behavior of the whole structure. A more stable approach would be to average deformation across several nodes instead of using only the minimum and maximum positions. This would reduce the impact of local irregularities and provide a clearer picture of how the structure behaves overall.

B. Material Behavior Simplification

The lattice is modeled with simple spring-like behavior, but TPU may deform differently in real applications. The lack of material damping or nonlinear stiffness could cause the lattice to stretch more easily in the simulation than it would physically. Adding a simple form of damping or adjusting the stiffness of the beams during larger deformations could help the simulation behave more like the real material, without needing to introduce more complex material models.

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