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

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***Abstract*— This proposal will look into analyzing auxetic structures for the purposes of robotic skin. The unique property of a negative Poisson ratio gives the structures high energy absorption and low stiffness making it ideal in both interior and exterior protection as well as flexibility. Our project aims to analyze different types of auxetic structures in these qualities to determine their feasibility as a Robotic skin.**

I. Problem Statement and Motivation

Recent state-of-the-art humanoid robots increasingly feature robotic skins that serve both functional and aesthetic purposes. Examples include 1X Technologies' NEO and Figure AI's Figure 03. Beyond providing a consumer-friendly appearance, these skins play a critical role in absorbing shocks and protecting not only the users of delicate internal mechanisms, such as precision gears, sensors, and embedded electronics. Thermoplastic polyurethane (TPU) is one of the most widely used materials for fabricating soft robotic skins due to its low cost, ease of manufacturing, and mechanical robustness. It can be readily 3D-printed into various lattice geometries, allowing rapid prototyping and structural customization. These advantages make TPU an attractive choice for testing diverse mechanical configurations and evaluating material behaviors in flexible robotic applications. However, conventional TPU 3D-printed skins also exhibit strong elastic resistance and limited flexibility. When applied to bending joints, they often behave like torsional springs, generating unwanted restoring torques that interfere with the robot's motion. Continuous bending of such materials leads to high resistive forces, which can in turn widen the sim-to-real gap in learning-based control systems due to unmodeled elastic dynamics. To address this issue, we aim to explore auxetic materials that can achieve quasi-zero-stiffness behavior, allowing the skin to deform easily without accumulating internal elastic stress, while still providing effective shock absorption and structural integrity.

II. Background and Literature Review

3D-printed TPU lattice structures have been widely studied for their energy absorption and tunable mechanical properties. Their performance depends heavily on lattice cell topology: geometry, infill density, and printing parameters [1][2][3]. In regards to some considerations to consider in lattice cell topology is the complexity of the lattice structure in question. It has been observed that the more "complex" a structure is, the greater the reaction forces and the smaller the deformation factor in those structures made of TPU [4]. Research in additive manufacturing has demonstrated that certain lattice patterns can drastically alter the stress–strain response, enabling applications in cushioning, biomedical implants, and soft robotics.

Meanwhile, auxetic materials—materials with a negative Poisson's ratio—expand laterally when stretched and contract when compressed. This unique deformation mechanism gives them remarkable impact resistance [5], indentation resilience [6], and improved damping behavior [7] compared to conventional foams. Recent works have explored various auxetic geometries (re-entrant, chiral, rotating-unit, and star-shaped) to optimize flexibility and energy dissipation under dynamic loading.

One of the following papers demonstrates a method of analyzing auxetic structure in a two dimensional space to measure the Poisson's ratios and comparing the two structures [8]. The study shows the strength of the Poisson's ratio depending on the stiffness of the structure in both material and structure. The stiffer the structure of the lattice, the more reduced the Poisson ratio is.

Building upon these findings, we propose to examine how auxetic lattices can be integrated into robotic joint skins, particularly focusing on their ability to absorb shock while minimizing the restoring stiffness that typically resists bending motions. We will quantify how effectively different auxetic patterns can maintain mechanical compliance without sacrificing protection.

III. Proposed Approach and Anticipated Contribution

We plan to simulate multiple auxetic lattice geometries in 3D, evaluating their deformation, stress distribution, and stiffness response under applied loads. For initial testing, we will use the lattice structures using a network of elastic beams seen in Figure A. Once designed, it will measure out the following qualities:

- Apply compressive and bending forces at one end of the structure and measure displacement propagation across nodes on the opposite side.
- Quantify restoring forces when the load is released to determine the degree of quasi-zero-stiffness behavior.
- Compare energy absorption efficiency and recovery ratio across different lattice topologies and material parameters (e.g., thickness, unit-cell angle, infill density).

For the numerical simulations, the mechanical and physical properties of TPU 95A will be applied. The following

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parameters are based on standard test data from material datasheets (e.g., Ultimaker TPU 95A, BASF Ultrasint TPU):

TABLE I
TPU CHARACTERISTICS

Property	Symbol	Typical Value	Unit
Density	ρ	1.20	g/cm³
Young's Modulus	E	26 35	MPa
Poisson's Ratio	v	0.45	-
Tensile Strength at Break	σ_t	43-50	MPa
Elongation at Break	ϵ_b	450-580	%
Shore Hardness	-	95A	-
Glass Transition Temp.	T_g	-24	°C

These parameters will be used to define the beam element material behavior in the finite-element lattice model. The relatively low modulus and high elongation of TPU 95A make it suitable for flexible skin structures, allowing large deformations under low stress while maintaining durability and energy dissipation capacity.

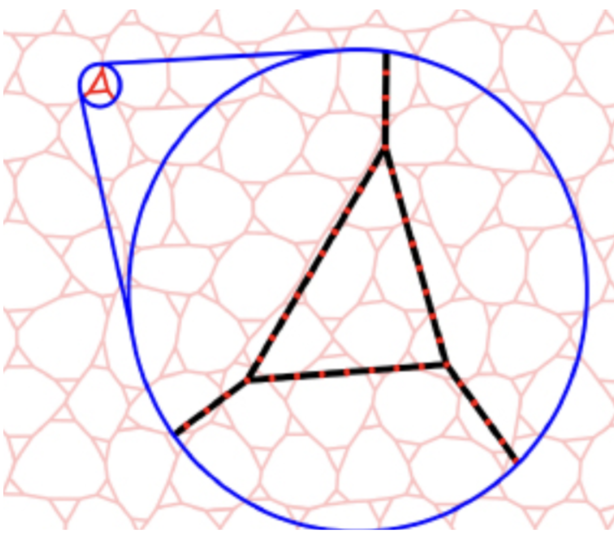

Fig. 1. The beam based approach of Lattice model [8]

The system should have the following parameters to consider to apply the measurements. The system beams should be designed with the material of TPU as mentioned before. The system should only use the external force applied to internal force and energy within the system. The structure should be fixed only on the other end of the structure and in the direction opposite to the load to apply the compression/expansion of the lattice structure.

$$F_{net} = F_{Load} + F_{vending} + F_{stretching} \tag{1}$$

$$nu = -\frac{du_y/dy}{du_x/dx} \tag{2}$$

$$SEA = \int F_{net} dx/m] \tag{3}$$

The code should loop over the Newton Ralphson implicit method function to measure the position change of the nodes and beams of the lattice structure. Key positions of the node to consider should be the initial positions before applied load, position of nodes steady state of the structure after applied load, and then steady state of the structure after releasing the load. The displacement of these positions will help to measure the Poisson's ratio, energy absorption, and the stiffness of the structures. Once the structures are implemented in a two dimensional space, the next test would be implementation of the skin within a three dimensional space.
The anticipated contribution of this study is to identify optimal auxetic designs that balance shock absorption and flexibility, thereby enabling future humanoid robotic skins that are both safe for human interaction and free of unwanted torsional stiffness at joints. This could significantly reduce the sim-to-real gap in reinforcement learning-based control and improve the mechanical performance of next-generation humanoid platforms.

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