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MECHANICAL PROPERTIES OF AUXETIC STRUCTURES: EXPLORING THEORY VS PRACTICE BY DESIGNING AND MANUFACTURING CURVED SURFACES USING AUXETIC UNIT CELLS.

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ABSTRACT

Current rapid design and fabrication techniques enable the creation of structures for a variety of applications: research, foldable robots, and art. However, these structural components are typically flat and rigid making it difficult to make curved structures. A recent area of research with the potential to address this problem are auxetics: mechanical structures made of repeating unit cells, basic building blocks composed of beams and hinges, to create unusual or counter-intuitive mechanical properties. When stretched, due to their structural design, auxetics have a volume increase which enables the formation of 3D curved surfaces from a 2D sheet of material. Work in the field of auxetics primarily focuses on creating and optimizing algorithms to generate auxetic designs. This work focuses on the mechanical properties of different auxetic structures so we gathered and synthesized information regarding mechanical characteristics of auxetics in a cohesive and presentable manner for quick reference. There are a variety of unit cell types discussed in literature. Applying knowledge of auxetics, different unit cells were manufactured to gather information such as: unit cell arrangements, deployed state, design limitations to compare theoretical and real life behavior. In theory assumptions do not affect deployment, but in practice they have implications. A half dome structure was created using different kinds of materials: cardstock, PET, and polyurethane foam to investigate how the formation of a 3D curved surface is influenced by material choice. Comparing the theory and practice of auxetic structures provides insight to motivate future research in applications of auxetics.

Nomenclature

Metamaterial: Metamaterials are artifically engineered materials which are designed to induced unique properties in a material that originally does not exist. Some unique properties: optical properties, structural integrity, and deployability. [23]

Auxetic: Structures which exhibit a negative Poisson's ratio that demonstrate counterintuitive behavior. [19]

Poisson's Ratio: The proportional decrease in lateral lenght to the the proportional increase in lenght when a speciment is subjected to tensile forces. A fundamental metric used to compare the performance of different materials. [6]

Deployability: The ability of a constructed structure to transition from one state to a desired state. In the realm of auxetics deployability refers to a structures ability to transition from a 2D sheet of material to a desired 3D curved surface.

Unit Cell: The basic building block used in the design of auxetic structures.

Introduction

Part 1: Background information, history

Design and manufacturing of robots is an increasing area of interest in robotics. The question: can we design 3D curved surfaces from 2D flat cut and fold patterns?, has garnered interest in the field of robotics in recent years. test fix

A particular area of interest is leveraging the concept of auxetics, particularly bistable auxetics to design a curved surface from a 2D sheet [4]. Bistable auxetics can be broken down to structures which have been designed with the intent of having a negative poisson ratio, and have two stable states: a deployed and undeployed state. [Get a source on auxetics definition]

There is an interest in auxetics as they are a solution to the problem of creating 3D curved surfaces from 2D elements. The ability to construct a 3D shape from a 2D object using: cuts, folds, links, pivots, etc., enables the design and fabrication of 3D structures [7].Another reason for interest in auxetics is because they offer a new manufacturing method. Current manufacturing methods like melt-extrusion are inefficient [12] because they not only create lots of wasted plastic, but also introduce anisotropic characteristics into the material which reduces the strength of the structures. Another benefit of auxetic structures is that unlike classical structures [to fill source from initial paper] they do not require external supports to remain stable once deployed.

Current work and Limitations

In the field of auxetics work has been done in creating and optimizing design algorithms [9] [16] [9] as well as looking at potential application of auxetic structures. From these design algorithms unique auxetic structures have been created and tested both in simulation and real world tests. Some objects which have been created are: vase, shoe, some, lighting shade, etc. From these works [8]. Works have also explored the potential of auxetics in potential future applications such as: deployable robots in outer space, mars structures, dynamic lighting, etc. [9]. Majority of recent work has been focusing on how to generate and optimizing the algorithms used to design bistable auxetic structures.

Limitations on current work include:overestimation of the energy required to buckle cells [4], constant mean stretch mappings have not be explored in depth [7] weakly bistable structures do not work well in simulation, behavior of the poisson ratio along and perpendicular to the curved surface is not known [12]. Simulation results are also limited due to assumptions and simplifications of structures [4] [12]. This work aims to focus on the mechanical properties of different auxetic structures and how these properties enabledifferent applications.

Project Scope

Creating a taxonomy for auxetic structures will enable the for the development of an application for an auxetic structure. This paper outlines an experimental study of auxetic unit cells, auxetic structures. This exploratory study is based on qualitative information, rather than then quantitative data as this was defined in the project scope. A future direction would be to conduct quantitative experiments, as will be discussed later. Presenting relevant information on the capabilities and limitations of auxetics in a clear and concise manner will enable individuals to make informed decisions as to which auxetics are better suited for certain applications.

Unit Cells

Auxetics, vary differently based on the way that they are constructed. A common mechanism in auxetics is a unit cell. A unit cell is the most basic building block in an auxetic structure. Unit cells can be further decomposed into a collection of beams and hinges which move as the unit cell is actuated. In the design of auxetic structures there is great variety in the kinds of unit cells used to make a structure. There are triangular unit cells [4], square unit cell [18], chiral structures [15], and many more.

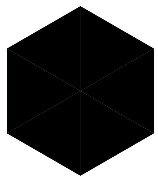
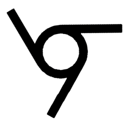
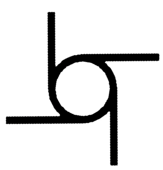
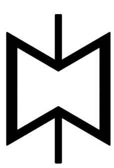
Triangular Unit Cell	Advantage	Disadvantage
	• Deployed Area is 4x original [4] • Can vary unit cell deployed state [18] [10]	• Point hinge assumption [18] • Determine hinge size
Tri-Chiral Unit Cell	Advantage	Disadvantage
	• Tolerate ↑ Range of Stress • Uniform Rotation [20]	• Requires Elastic Material • Cylinder Rotation Limits deployment [15]
Chiral Square Unit Cell	Advantage	Disadvantage
	• ↑ Auxetic Effect • Simple Repeatable Pattern [21]	• Ligament Limit [18] • Hinges Weak Point of Cell [15]
Tetra-Chiral Unit Cell	Advantage	Disadvantage
	• ↑ Auxetic Effect • More Links = Lower Stress [20]	• Ligament bending [15] • Ligament Limit [18]
Re-entrant Square Unit Cell	Advantage	Disadvantage
	• Most well known • Simple Actuation	• Needs rigid material • Difficult to manufacture on commercial scale [15]

TABLE 1. Auxetic unit cell geometry with advantages and disadvantages

I found triangular unit cells mentioned most frequently in auxetic literature. The following literature mentions the use of triangular unit cells: [4]. These kinds of auxetic cells are unique in the sense that they are triangular and they are connected to each other with out defined beams rather than are connected to one another. These unit cells can achieve large amounts of deployability due to the assumption of point hinges. This assumption, although it has large benefits has its limitations which will be further discussed down below.

Chiral unit cells are constructed from nodes which are connected by straight links. The nodes can either be circular or rectangular. The main defining feature of chiral unit cells is that when actuated all links rotate in the same direction (either all clockwise or counter-clockwise). As stated in [15], auxetic structures made from chiral unit cells maintain their auxetic capabilities for strains in a large range. Meaning that chiral unit cells are able to withstand larger amounts of strain and still exhibit a negative Poisson's ratio.

There are various kinds of re-entrant unit cell geometries used to create auxetics structures, but the most commonly known one is the Re-entrant square unit cell. As depicted in Table 1. the re-entrant square unit cell is made up of beams connected by hinges. It is these beams and hinges which create a behavior of increasing cross sectional area when stretched, a property that is not commonly found in nature.

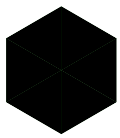
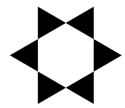
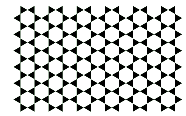
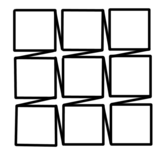
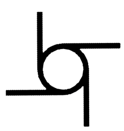
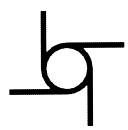
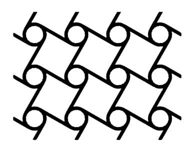
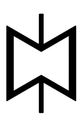
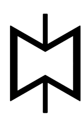
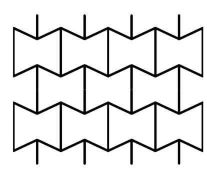
Unit Cell	Deployed Unit Cell	Repeated Array
		
Chiral Square Unit Cell	Deployed Unit Cell	Repeated Array
		
Tetra-Chiral Unit Cell	Deployed Unit Cell	Repeated Array
		
Re-entrant Square Unit Cell	Deployed Unit Cell	Repeated Array
		

TABLE 2. Auxetic unit cell geometry, deployed state, and repeated array

Mechanical Properties

Here is where I will write about the mechanical properties which have been tested for auxetics. If possible in my work and I am able to create an auxetic structure then I will also include my results for those tests. If I am not able to I will include information about different mechanical properties which are "important" and I will also explain why those mechanical properties are important

Methods

A literature review is conducted to gather information on the different kinds of auxetics structures that have been designed and tested. Work in the field of auxetics primarily focuses on creating and optimizing algorithms to generate auxetic designs. This work focuses on the mechanical properties of different auxetic structures so we gathered and synthesized information regarding mechanical characteristics of auxetics into a table for quick reference. A select few of unit cells were manufactured and tested. These unit cells were not manufactured as individual unit cells rather they were manufactured as cell arrangements. The unit cells that were tested are presented in 1 and 2. As many mechanical properties are influenced by the material used to create a structure different materials were investigated. For unique and material

Design of Auxetics

An auxetic structure was designed using the software called Rhinoceros 3D (Rhino 7). Rhino 7 is a computer-aided design software that is used for creating, editing, animating: solids, surfaces, meshes, and lots more. For the design of auxetic cells, the grasshopper plugin used in the paper [4]. Two kinds of auxetic cells were able to be rendered using the grasshopper plugin. The first of the two was the triangular auxetic cell presented in tables 1 and 2. The second auxetic unit cell were bistable auxetic surface structure cells $(BASS\_cells)$. Both of these unit cell types were discussed in [4]. The remaining designs presented in tables 1 and 2 came from different papers [20] [18] [15]. Available code to make structures out of these auxetic unit cells was not used because of software accessibility. The paper [20] discusses and Abaqus plugin that can not only be used to create designs out of chiral and re-entrant unit cells, but their performance can also be evaluated. (The future use of this plugin will be discussed in a later section.) When designing the following unit cells: Tri-Chiral, Chiral Square , Tetra-Chiral,and Re-entrant Square the software known as Inkscape was used to draw and make individual unit cells. Inkscape was used as opposed to other software such as Silhouette Studio, because of the broader capabilities provided. The designs presented in 1 were individually created withing Inkscape. Once each unit cell had been designed they were repeated to create the repeated arrays that can be seen in 2. As per reference to the paper [18] these auxetic unit cells were generated by repeating unit cells and making sure that each unit cell was connected to it's neighboring unit cells. In each repeated array the size of each unit cell remained constant so that forces would be evenly dispersed to avoid any stress concentrations.

Aside from rendering auxetic cells, a 3D structure of a dome was designed and simulated using triangular auxetic unit cells. The simulation revealed the behavior of the auxetic structure during the transition from it's undeployed state to its fully deployed state. The simulation was used as way to identify what sort of behavior one might expect after manufacturing an auxetic structure.

FIGURE 1. This is a half dome which was modeled within Rhino 7. This design was then used to create 2

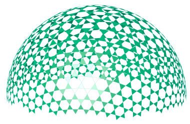


FIGURE 2. Perspective view of Auxetic Dome Fully Deployed: Made using Triangular Auxetic Unit Cells.

Manufacturing/Building Process

The auxetic cells and 3D structure were manufactured using flat sheets of three different types of material. Cardstock, Polyethylene terephthalate (PET), and Polyurethane foam were the three materials which were tested. These materials were selected for a variety of reasons. The cardstock was chosen because it is a material that is easily accessible compared to the other two materials. Accessibility of auxetic designs was a secondary focus in this focus and using cardstock was a good way to explore the behavior of auxetic cells and structures if a cheaper material was used. PET was chosen because it is of similar thickness to the cardstock, however it is a lot more rigid meaning that it will not tear as easily. Lastly, the Polyurethane foam was selected as it was hypothesized that materials with more elastic properties would display better auxetic behavior, the elastic properties would allow for the hinges of the unit cells to deform and return to their initial state.

For the manufacturing that made use of both the cardstock and PET a Silhouette Cameo 4 was used. The material thickness and intricacy of design make it difficult for these designs to' be cut by hand.

Results

From 2 the Tetra-Chiral Unit Cell and Chiral Square cell repeat arrays were manufactured using cardstock, PET sheets, and the polyurethane rubber. Aside from these unit cells Hexa-Chiral unit cells (circular unit cells with 6 beam links connecting to other unit cells) and Chiral Hexagon unit cells (similar to the Chiral Square cells but instead of squares the basic unit cell is a hexagon)

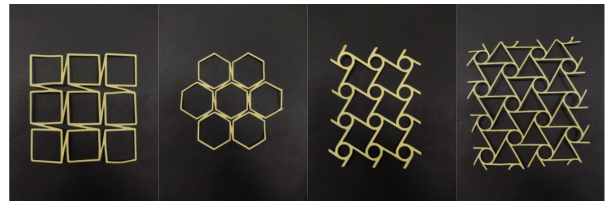


FIGURE 3. Arrangement of repeated cell arrangements manufactured using cardstock. From left to right: Chiral Square, Chiral Hexagon, Tetra-Chiral, Hexa-Chiral.

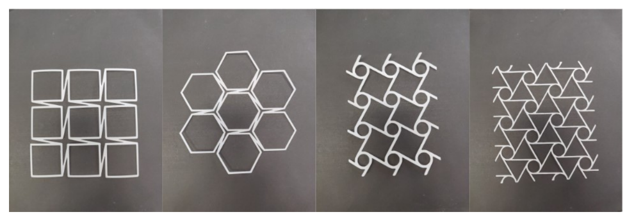


FIGURE 4. Arrangement of repeated cell arrangements manufactured using Polyethylene terephthalate (PET) . From left to right: Chiral Square, Chiral Hexagon, Tetra-Chiral, Hexa-Chiral.

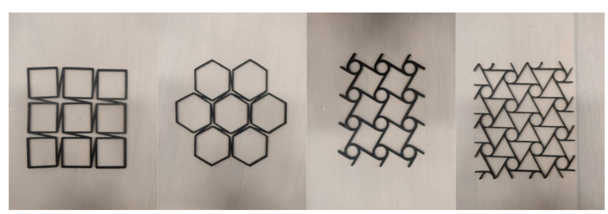


FIGURE 5. Arrangement of repeated cell arrangements manufactured using polyurethane rubber. From leftto right: Chiral Square, Chiral Hexagon, Tetra-Chiral, Hexa-Chiral.

As stated previously a different version of grasshopper plugin from [4] was used to manufacture auxetic cells. The auxetic cell which was used to manufactured the dome structure presented in 2. The aux_cell discussed in [4]. The aux_cell is a triangular unit cell. The initial designs did not work straight from the plugin and additional modification in the .dxf files was required for a working auxetic cell to be manufactured.

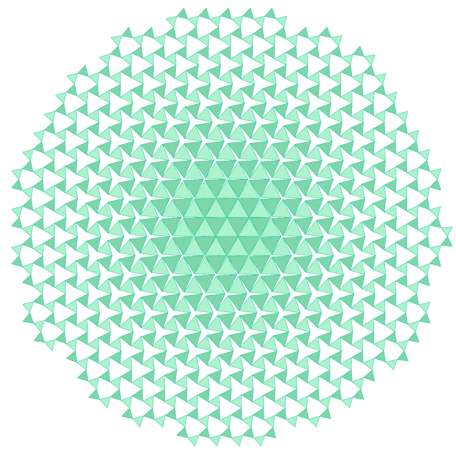


FIGURE 6. Perspective view of Auxetic Dome: This is a top view of what the 2 Dimensional cut out design for the auxetic dome presented in 2. This top view highlights how in a 2D state there exists variable deployability amongst the unit cells that make up this structure.

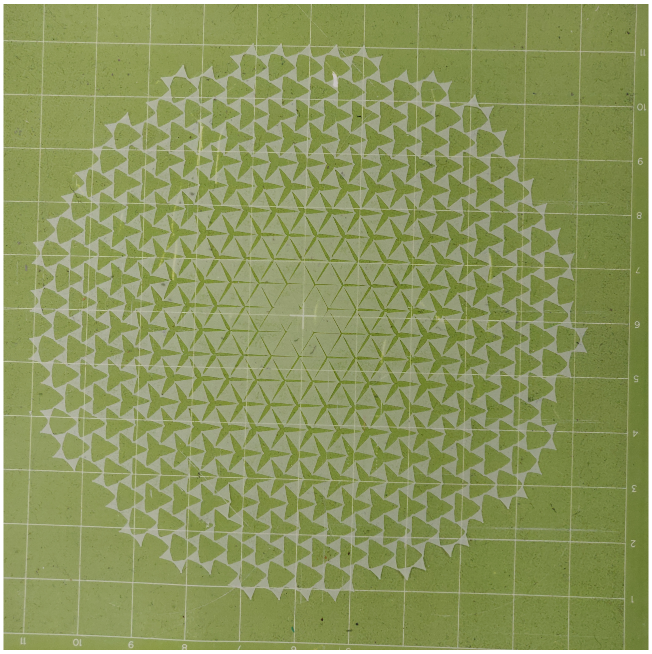


FIGURE 7. 2D sheet: Dome Auxetic Top View (PET)

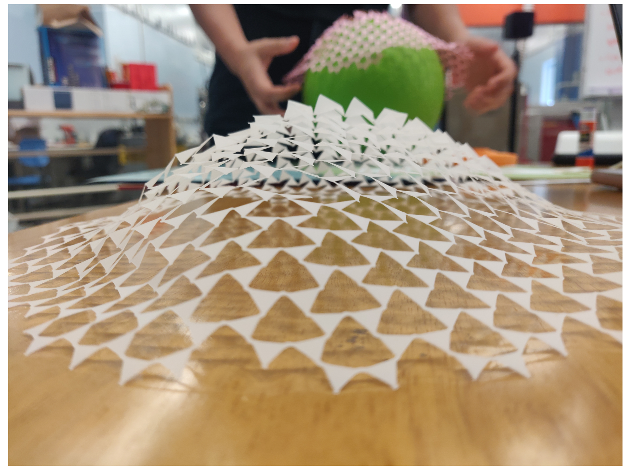


FIGURE 9. Auxetic Dome Deployed (PET)

FIGURE 10. Auxetic Dome Deployed (PET)

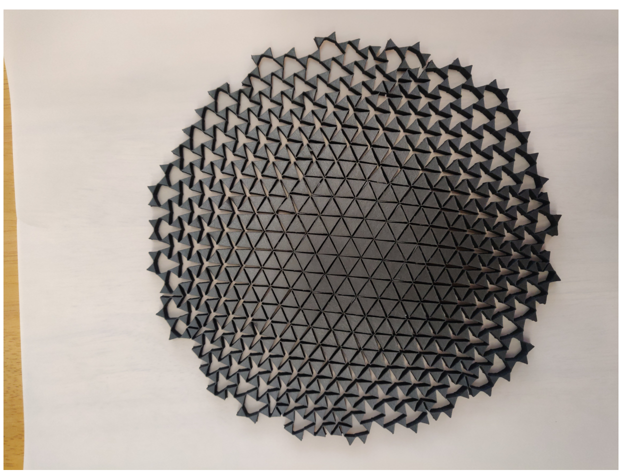


FIGURE 8. 2D sheet: Dome Auxetic Top View (Polyurethane Foam)

By comparing 6, 8, and 7 we are able to see that the design remained relatively similar. This was expected as a laser cutter was used to manufacture the Polyurethane rubber and a paper cutter was used to manufacture the design that used the PET paper. One interesting observation is tha the Polyurethane rubber was a lot more flexible in this top view. By inspecting 8 we can see that the design has a lot more freedom and tha the design looks a bit shifted due to this extra freedom. The design which was constructed using PET paper was a lot more rigid and did no allow for movement of the unit cells in this 2D state. In 9 and 10 we can see the deployed state of the dome using the PET and the rubber. From visual inspection it can be seen tha that both materials are able to achieve a dome like resemblance, however the rubber dome displays greater curvature in comparison to the dome made out of PET.

Application

Applications which have been explored

There are many applications for which auxetic structures have been used. The paper [8] discussed some applications of auxetic structures beyond simple curved surfaces. A shoe, specifically a high heel shoe, was created using the triangular auxetic unit cell pattern which was discussed in 1 and 2. The shoe auxetic design is metallic and makes use of auxetics properties to create complex curved structures that have multiple curves. The 2D sheet of metallic material was able to be deployed into a high heel shoe. Aside from the shoe, an article of clothing was also designed and created using the same auxetic design. The piece of clothing is a top and was manufactured using leather. Both of these applications highlight auxetic structure's ability to form continuous 3D shapes from 2D sheet of material.

Commercial applications of auxetics has come in the form of Fundamental Berlin Push Bowls. These are special kind of bowls which arrive as simple sheets of: copper, shiny brass, stainless steel, and even blue steel. The 2D sheets of material are deployed into their 3D structure via light pressure actuation. The customer can use their hands to apply pressure to the 2D disk. The result is a 3D structure of a bowl which can be used to store small items: rings, bracelets, keys, etc. These unique bowls come at a variety of price ranges and let customers experience a deployable auxetics structure firsthand. The website contains more information about push bowls.

Auxetic patterns have also been used in shoes, furniture, and other sportswear [17]. A sports sleeve which deploys via thermal actuation has been developed for better breathability when playing sports [22]. This type of application lies within the field of smart materials which adapt and transform depending on the type of environment in which they are in. Thermal actuation can be used to make clothing that changes based on the temperature to allow the body to cool down and prevent heat related problems such as heat exhaustion and heat stroke [11]. Auxetics used in furniture are a promising field because of the deployability of auxetics. Furniture can be shipped out as flat sheets of material and the consumer can simply deploy them into their prescribed 3D configuration. Another benefit to using Auxetics for furniture is the deformable capabilities of auxetics. When a person sits on a chair they apply a force on the point of contact, and with auxetics the chairs structure can adapt based on the person sitting down for a more enjoyable experience.

Potential Applications

Use of auxetics in the biomedical field is something that exists and is continuously being explored because of its potential benefit [14] [19]. Dilators with an auxetic cover are used to open cavities of an artery is an interesting application [5]. Additional directions for biomedical devices that incorporate auxetics are smart filters [14] because of an auxetic structure's ability to open and close spaces between individual unit cells. With this an auxetic structure can be used to administer treatment to a patient over a period of time. As the auxetic structure expands or contracts the amount of administered medication would differ. As discussed previously some auxetic structures can be thermally actuated, presenting a way to achieve a variable filter made of auxetic components.

Auxetics can also be used in the aerospace and space industries due to the capabilities: deployability, light weight, and ability to model different curvatures [1]. These characteristics make auxetics valuable in the aerospace field where it is important to have low material usage and cost [2]. A few particular use of auxetics in the aerospace industry would be filters, film, space suit cushioning, packaging, utensils, etc. The deployability of auxetic structures would allow for sheets of material to be pulled and deployed into a variety of objects that might otherwise be too heavy or take up too much space in a space mission. Deployable pots, tools, and even bowls as discussed in [8] are all a possibility with the use of auxetics.

Discussion

Future work in auxetic mechanical properties will involve quantifying auxetic performance. This experimental study used qualitative approach, an exploratory approach, rather than a quantitative study. Having qualitative data would result in greater verifiable reproducibility of future work as there would be a well defined parameter that can be be verified.

Other materials different than cardstock, PET, and Polyurethane rubber will be tested in order to determine what other types of materials are suitable for auxetic design. In addition, to determining suitable materials, using different materials could open a future avenue of making composite auxetics which are designed with multiple materials. Well suited materials could be used for hinges and cheaper more accessible materials could be used for the beam components of auxetics.

Aside from the potential areas of future direction mentioned above exploring how auxetic designs and structures can be implemented into current cut and fold robot software such as RoCo. RoCo allows users to not only design high level parameters of a structural component, but also provides the user with the necessary blueprint to make their designs a reality [13]. The blueprints have instructions on how to cut and fold the design and any electronic wiring directions. The user starts by thinking of what motions or capabilities they want their design to achieve as well as what shapes and modular components can be used to achieve them. Like other cut and fold robotic software it is difficult to generate different kinds of curved surfaces using RoCo. Another limitation of RoCo that plays an important role in this is the difficulty of making small scale designs due to difficulty in using tabs for such small structural components. By implementing auxetic design into RoCo, 3D curved surfaces would be an additional aspect to robot designs leading to the creation of more unique and interesting robots. A possible use for auxetic designs in cut and fold robots is spherical wheels which can be controlled to allow for locomotion in all directions. Cut and fold robots are typical created using thin material like cardstock or PET. Materials like wood which are too rigid, unable to fold them, then laser cutting would be the manufacturing method. From our experimental study auxetics were created using both a paper cutter and the laser cutter which are typical methods in which components in RoCo are manufactured. Another capability of RoCo is that it lets the user know when a design is not feasible or if there are errors in the design of the structural components. Not only would be beneficial to incorporate auxetics designs into RoCo because it increases the variety of robotic structure which can be created, but they can also make use of the computational viability to verify the realization of structures from 2D to 3D.

[3]

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