A Concise Review of Kirigami Inspired Actuation and its Potential use in Surgical Environments

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April 30, 2020

Abstract

A concise review of kirigami inspired actuators developed for potential use in surgical devices and medical robotics is presented in this paper. Novel research involving pneumatic and mechanically induced actuation is explored. The effects of specific geometries and configurations of current actuators and graspers is covered. The initial goals of developing a novel inflatable kirigami pattern for a pneumatically actuated endoscopic arm was not achieved under current circumstances and university facility closures. However, the original project design methods, and a review of current kirigami actuator design and testing methods are discussed. Simulation approaches of testing are also discussed. This paper addresses the challenges of efficient tissue manipulation and surveys literature related to inventing and implementing actuators and graspers for surgical robotics and laparoscopic or endoscopic procedures.

1 Introduction

Current surgical manipulation tools pose numerous challenges, specifically during laparoscopic and endoscopic procedures. Sharp end-effectors, graspers, and manipulation tools lead to tagging of soft tissue and damage to surrounding healthy tissue and vessels. Majority of manipulation and grasping tools in the medical industry are designed using stainless steel or titanium. Their rigid structures impede their ability to access, propagate, and easily navigate soft tissue environments. Current endoscopes and laparoscopic instruments also lack sufficient articulation and degrees of freedom. Thus it is crucial to develop tools with greater degrees of freedom with soft, flexible, lightweight materials. There are various studies which aim to derive solutions to surgical challenges by designing tools that exhibit these material and mechanical properties.

2 Kirigami

Origin

Kirigami, similar to Origami, is the ancient Japanese art of adding cuts and folds to paper to produce 3-Dimensional geometric shapes and designs from 2-Dimensional materials. The ability to produce 3-Dimensional structures at low cost from 2-Dimensional materials purely through mechanical stimuli has led to various novel manufacturing methods and applications in bio-inspired design, optoelectronics, and programmable membranes [1]. A study in collaboration with the University of Illinois – Urbana Champagne and Northwestern University designed predictable nano-scale and meso-scale 3D structures using kirigami membranes of silicon, metal, and various polymer materials [2]. The study found that this predictable morphology phenomenon was consistent across a wide range of materials and length scales. Depending on the mechanical force applied, the materials can also reconfigure into their original shape when the load is removed. Their findings were significant because it unleashed the potential of using kirigami to tune metamaterials using specific geometries [3-4]. The fact that the articulation and mechanical outcome of kirigami sheets is material and scale independent, kirigami can be used to mechanically manipulate materials used in microelectromechanical systems, soft robotics, and biomedicine [3].

Linear Cut Patterns

There is ample research incorporating the use of kirigami in optoelectronics and wearable electronics. The ability to create tunable surfaces on material led to the development of kirigami solar cells which can be angled and controlled to face the sun by use of an optical tracking system [5]. Linear cut patterns were tested on lab fabricated epitaxial layers of p-n junction gallium arsenide active material. The kirigami geometry was defined by cut length (L_c), the spacing between the cuts in the axial (y) and transverse (x) direction. The change in feature angle was defined as(θ). The feature angle can be predicted using the decrease in width of the kirigami sheet as a result of transverse strain (ε_T) as a function of axial strain (ε_A) [5].

$$\theta = \cos^{-1}\left(\frac{1}{\varepsilon_A+1}\right) \tag{1}$$

$$\varepsilon_T = \frac{R_1-1}{R_1+1}\left[\cos\left(\sin^{-1}\left(\frac{2R_1\tan\theta}{R_1R_2-R_2}\right)\right)-1\right] \tag{2}$$

The equations that are used to define variables R_1, R_2, ε_T, and ε_A are as follows: $R_1 = \frac{L_C}{x}$, $R_2 = \frac{L_C}{y}$, $\varepsilon_A = \frac{L-L_0}{L_0}$, $\varepsilon_T = \frac{W-W_0}{W_0}$ [5]. The derivation of the equations (1) and (2) can be found in the supplemental material section (Supplement Note 1).

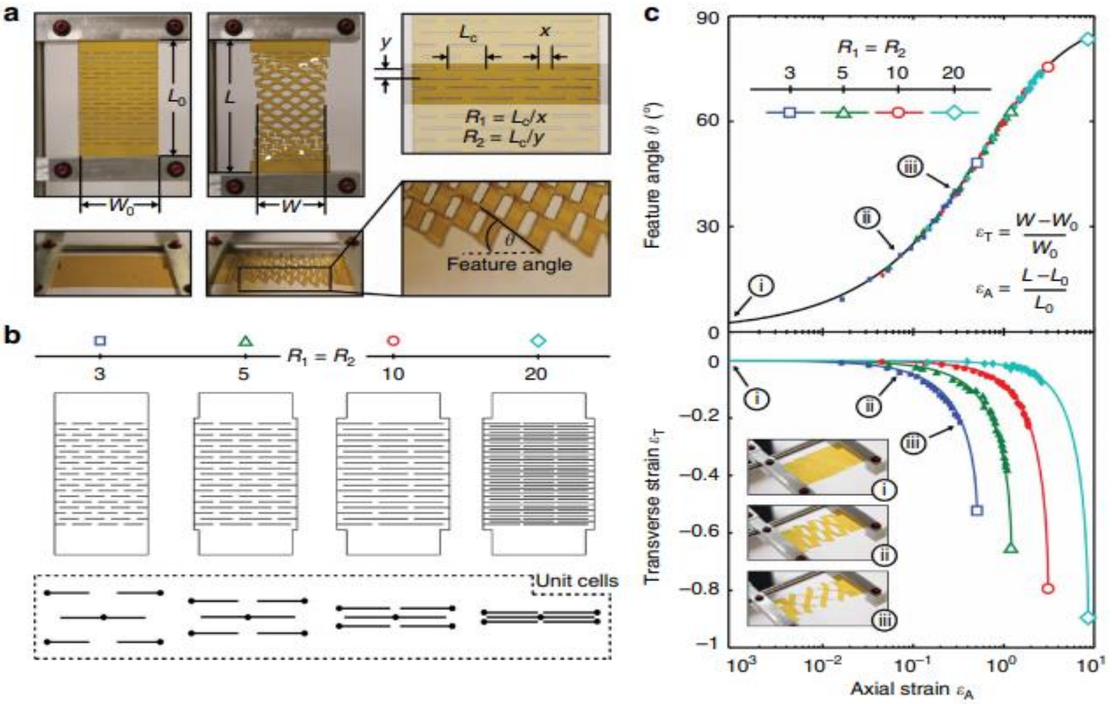


Figure 1. (**a**) The variables L_0 and W_0 are defined as the original length and width of the Kirigami sheet. Variables R_1 and R_2 are defined as the ratios of cut length to the transverse and axial distance between the cuts. The feature angle θ is indicated in the image. (**b**) This study tested four different values for R_1 and R_2, assuming $R_1 = R_2 = 3, 5, 10, 20$. The cut geometries for these values are

depicted. (**c**) The feature angle remains the same regardless of changes in cut geometry ratios. As the values for R_1 and R_2 increase, the transverse and axial strains also become greater. This image was reprinted from [5].

These findings are significant because it can help predict the feature angle as well as changes in height and width of the kirigami sheet based on axial and transverse strains. This gives the ability to design specific tunable surfaces using varying linear kirigami cut spacing, as well as the ability to understand how the cut geometry affects the elasticity of the overall kirigami sheet. Further studies investigating the symmetry, asymmetry, and coexistence of co-linear kirigami cut patterns using polyethylene terephthalate (PET) sheets show that the stiffness of the sheets can be changed by manipulating cut geometry [2-8]. The addition of minor cuts perpendicular to the major co-linear cuts significantly reduces stiffness in the kirigami sheet (Figure 2) [6]. Based on these conclusions, unique patterns can result in varying stiffness of sheets. This is extremely advantageous when developing tunable surfaces, actuators, and graspers because even if these items are manufactured from the same material, in this case PET, they can be designed to exhibit different mechanical properties simply with varying cut patterns in specific locations.

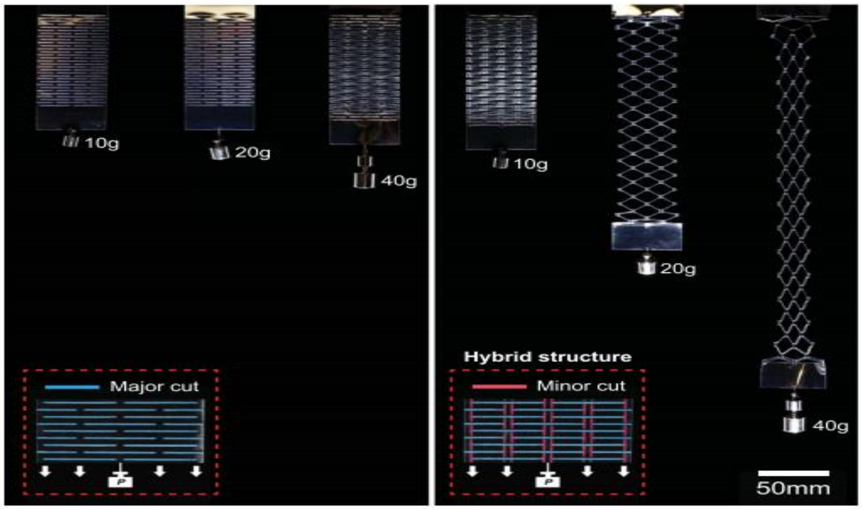


Figure 2. Kirigami PET sheets with only major ‘blue’ cuts (left) and with major ‘blue’ and minor ‘red’ cuts (right) are depicted. Masses of 10g, 20g, and 40g are attached to the PET sheets. The sheet with minor and major cuts exhibits significantly lower stiffness than the sheet with only major cuts. This image was reprinted from [6].

Relevant Studies

Research geared towards applying kirigami to develop bio-inspired robots, graspers, and actuators for potential surgical use is a fast growing field. MOSS Lab at Boston University applied the concept of linear kirigami cuts to a curved PET shell [9]. The grasper is capable of precisely grabbing and lifting objects of various sizes and shapes while requiring a low mechanical stimulus. This design can be tested with different biocompatible or soft materials which will potentially allow for its use as a biopsy tool or gripper for tissue manipulation in a surgical environment.

Meanwhile, the Bertoldi group at Harvard University in conjunction with the Wyss Institute developed a bio-inspired kirigami pneumatically actuated snake skin [10]. The study tested four different kirigami cut patterns which were laser cut onto polyester plastic sheets. The four patterned skins consisted of linear, circular (half- circle), triangular, and trapezoidal cuts (Figure 3). The patterned polyester skins covered a triangular hollow soft, fiber-reinforced elastomeric actuator. The snake was powered by a lithium ion battery and propelled itself by pumping air into the silicone rubber tubing. All skin geometries were tested by pneumatically actuating the snake by pumping six cycles of air across a horizontal and inclined surface. The study concluded that the trapezoidal kirigami pattern resulted in the greatest elongation, and displacement after 6 pneumatic cycles. It also displayed the highest friction coefficient, resulting in a more efficient crawling motion (Figure 3).

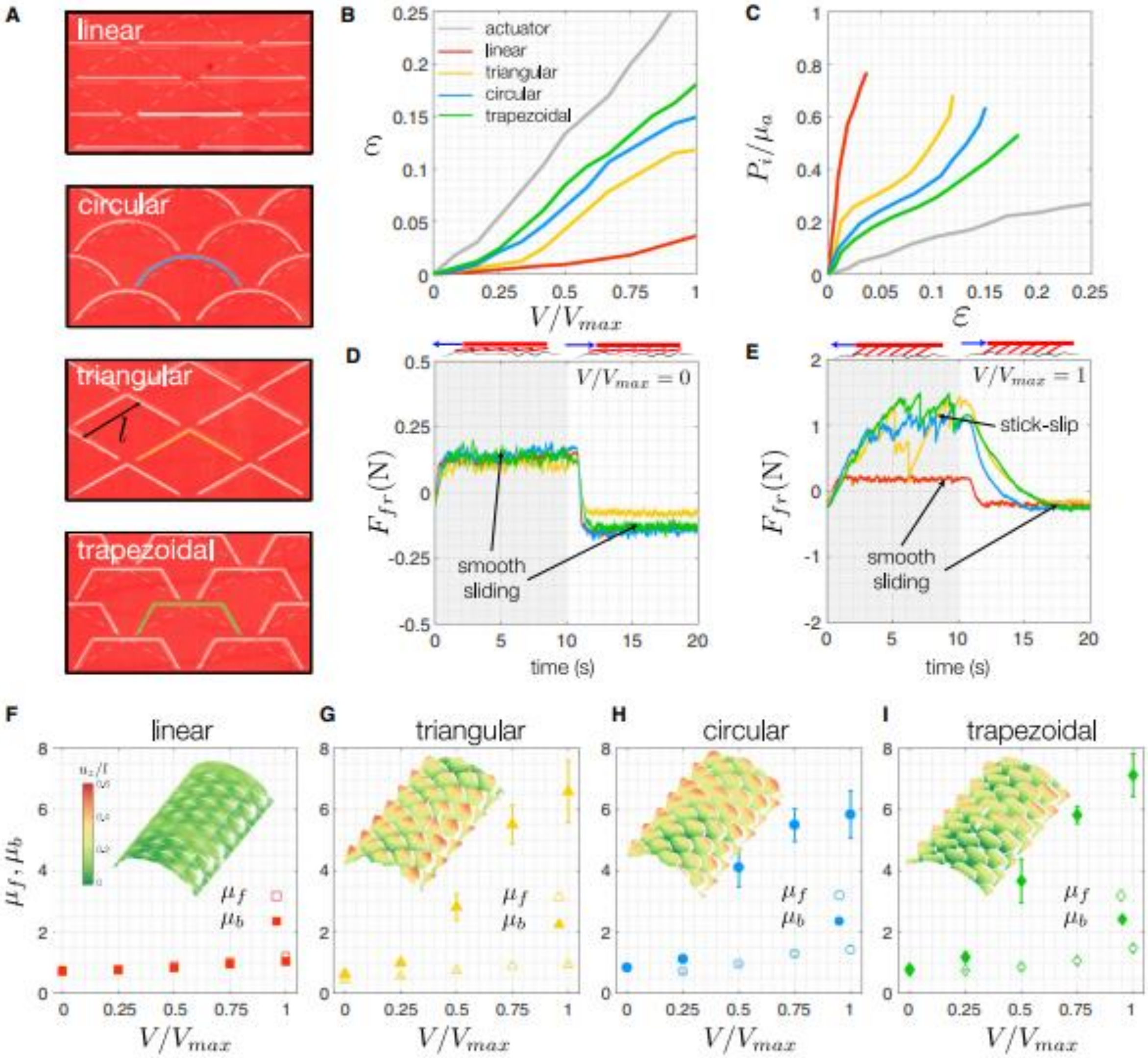


Figure 3. (**A**) Cut geometries for snake skin. (**B**) Graphical representation of elongation of snake skins. (**C**) Graphs of pressure normalization after actuation. (**D**) Friction measured in direction of movement (**E**) Friction measured in the opposite direction of movement. (**F-I**) 3D-scanned surface profiles of snake skins based on cut geometry, at full volume. The image was reprinted from [10].

Understanding the propagation and elongation properties of different circular, triangular, and trapezoidal cuts will enable researchers to create more diverse designs for more movement variability.

Similar to many inflatable origami actuator studies, the Bertoldi group conducted a novel study to develop inflatable kirigami actuators [11-12]. The model design was similar to the snake skin robot, however, it was an inverted version of the pneumatic snake. The kirigami polyester shell was wrapped and sealed in a thin soft silicon rubber and was pneumatically actuated [12-13]. The kirigami cylinders had linear cut geometries which allowed them to vary in stiffness. As air was pumped into the kirigami cylinder the device was able to bend in the desired direction, ultimately based on its kirigami pattern and the pressure driving the motion.

Figure 4. An example of inflatable kirigami actuators developed by Dr. Antonio Elia Forte, a Post Doc working on the project. This image was taken from Dr. Antonio Elia Forte's personal website, under research interests, architecture materials [13].

3 Initial Project Design

The initial aim for my term project was to develop a kirigami mechanism based actuator with improved degrees of freedom and accessibility for potential use in surgical environments, specifically endoscopic or laparoscopic procedures. I wanted to explore and execute the design and manufacturing process of an inflatable kirigami actuator with the ability to articulate and propagate through an environment that mimicked the jejunum. After reviewing literature and relevant studies, I wanted to incorporate varying cut shapes and cut geometries in my design to achieve the mechanical goals. Unlike the inflatable kirigami study conducted at Harvard University, I wanted to experiment with the use of trapezoidal cuts on inflatable kirigami instead of simply linear cuts, since trapezoidal cuts exhibited the most crawl in the kirigami snake skin study. I wanted to experiment with changes in stiffness by combining linear, circular, triangular, and trapezoidal cuts and modifying the cut length (L_c), and the spacing between the cuts in the axial (y) and transverse (x) directions. I wanted to then calculate the feature angle (θ) and the transverse strain (ε_T) as a function of axial strain (ε_A) using equations (1) and (2) defined above. Sides or specific surfaces of the kirigami tube that had a pattern which exhibited lower stiffness than the opposing surface would have articulated towards the direction of the lower stiffness pattern. Thus, the articulation and propagation of would be controlled by the tunable surface of the kirigami tube. I had decided on utilizing the conventionally used PET as the kirigami sheet material and thin silicon film to externally seal the kirigami tube. I was going to pneumatically actuate the kirigami tube using a syringe, or if time and equipment permitted, design a controller run on a lithium ion battery similar to the pneumatic snake skin actuator design. I wanted to make additions to my design by attempting to simultaneously actuate multiple kirigami tubes in different directions based on patterns, while using the same syringe or pneumatic pump. However, due to current circumstances and university closures, I was not able to actualize my designs or methods.

4 Alternative Methods and Original Contributions

I decided on a simulation based approach to design my initial project idea using COMSOL Multiphysics software. I was determined to design a 3D working model of an actuating inflatable kirigami tube. I experienced many difficulties while connecting to COMSOL v5.4 using Citrix. I was able to get access to COMSOL v5.0; however, some of the drawing tools and model settings did not overlap. I continued to attempt to make progress at developing a model reflecting my initial project idea. However, it was unsuccessful. I could not find specific tutorials which had instructions explaining how to simulate one inflatable material inside of a more rigid plastic body. I was also having difficulty mirroring the rows of cuts that I had initially drawn. Along with COMSOL, I have been working on a code based approach to design kirigami patterns using Python 3 in Jupyter Notebooks. The goal is to create an easy user friendly GUI which prompts the user to input pattern shapes and geometries, including a sheet outline. Ultimately, the goal is to be able to generate intricate kirigami patterns and export the images as .esp files to send directly to the laser cutter for efficiency. I will be using this in my future research which is related to kirigami and its applications in surgical tools. Thus far, I have been able to generate co-linear cut patterns in which the variables cut length, the spacing between the cuts in the axial and transverse direction, cut overlap, and cut width are customizable and user defined. I have also been experimenting with ellipsoidal cuts to determine how to customize and combine circular cuts in the program.

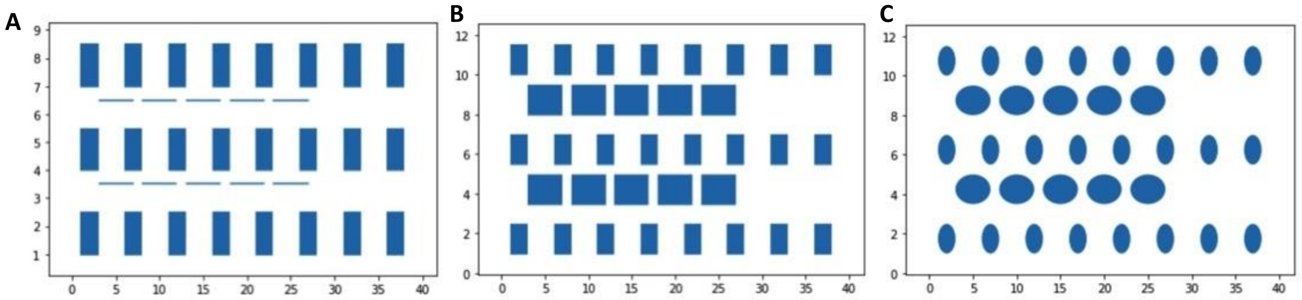


Figure 5. (**A**-**B**) Customizable co-linear cut patterns. (**C**) Customizable ellipsoidal cut pattern. The code for these figures can be found in the supplemental material section (Supplement Note 2).

5 Concluding Remarks

This paper successfully covers recent studies and research related to tunable surface kirigami and its application in actuators with the potential for surgical use. Although I was unable to design a final product or create a 3D simulation depicting an inflatable kirigami actuator with varying surface patterns, the potential methods and ground work for a feasible project is explained. The mechanical behavior and relationships are concisely described and cited with proper sources. The broader impacts of tunable kirigami surfaces are discussed. Cut geometries can be introduced to soft biomaterials to develop better articulating robotic arms for surgery which will drastically reduce unnecessary tissue damage. The immediate next steps towards designing the initially proposed actuator is to continue to read literature, develop a functional working model in COMSOL

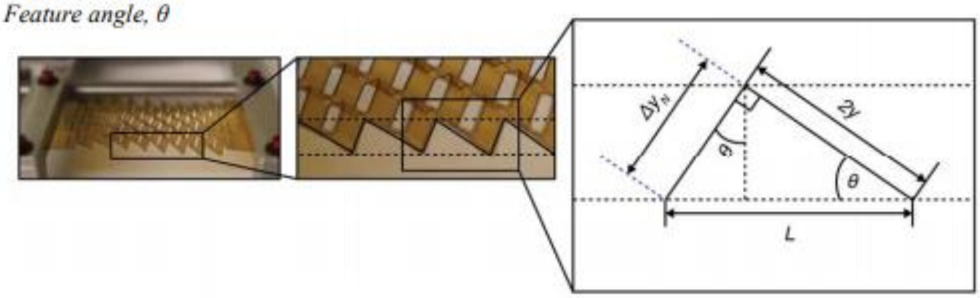
Multiphysics, and finally create a user friendly GUI which allows for fast, customizable pattern generation which can be directly sent to a laser printer or modeling software. Further investigations in this field which combine biocompatible materials with novel tunable surface patterns will continue to be underway. The integration of kirigami in soft robotic actuators holds the future to developing light weight, articulating, surgical and medical devices.

6 Supplemental Material

Supplement Note 1 [5]

Derivation of geometric response

Feature angle, θ



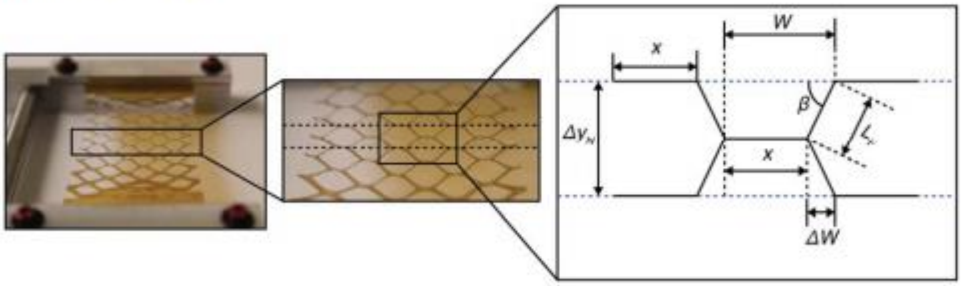
$$L_0 = 2y \tag{1}$$

$$L = \frac{2y}{\cos\theta} \tag{2}$$

$$\Delta y_N = 2y\tan\theta \tag{3}$$

$$\varepsilon_A = \frac{L - L_0}{L_0} = \frac{1}{\cos\theta} - 1 \quad \rightarrow \quad \theta = \cos^{-1}\left(\frac{1}{\varepsilon_A + 1}\right) \tag{4}$$

Transverse strain, ε_T



$$W_0 = x + L_F \tag{5}$$

$$W = x + \Delta W \tag{6}$$

$$\varepsilon_T = \frac{W - W_0}{W_0} = \frac{L_F\cos\beta - L_F}{x + L_F} \tag{7}$$

where:

$$\Delta W = L_F \cos\beta \tag{8}$$

$$\beta = \sin^{-1}\left(\frac{y\tan\theta}{L_F}\right) \tag{9}$$

$$L_F = \frac{L_C - x}{2} \tag{10}$$

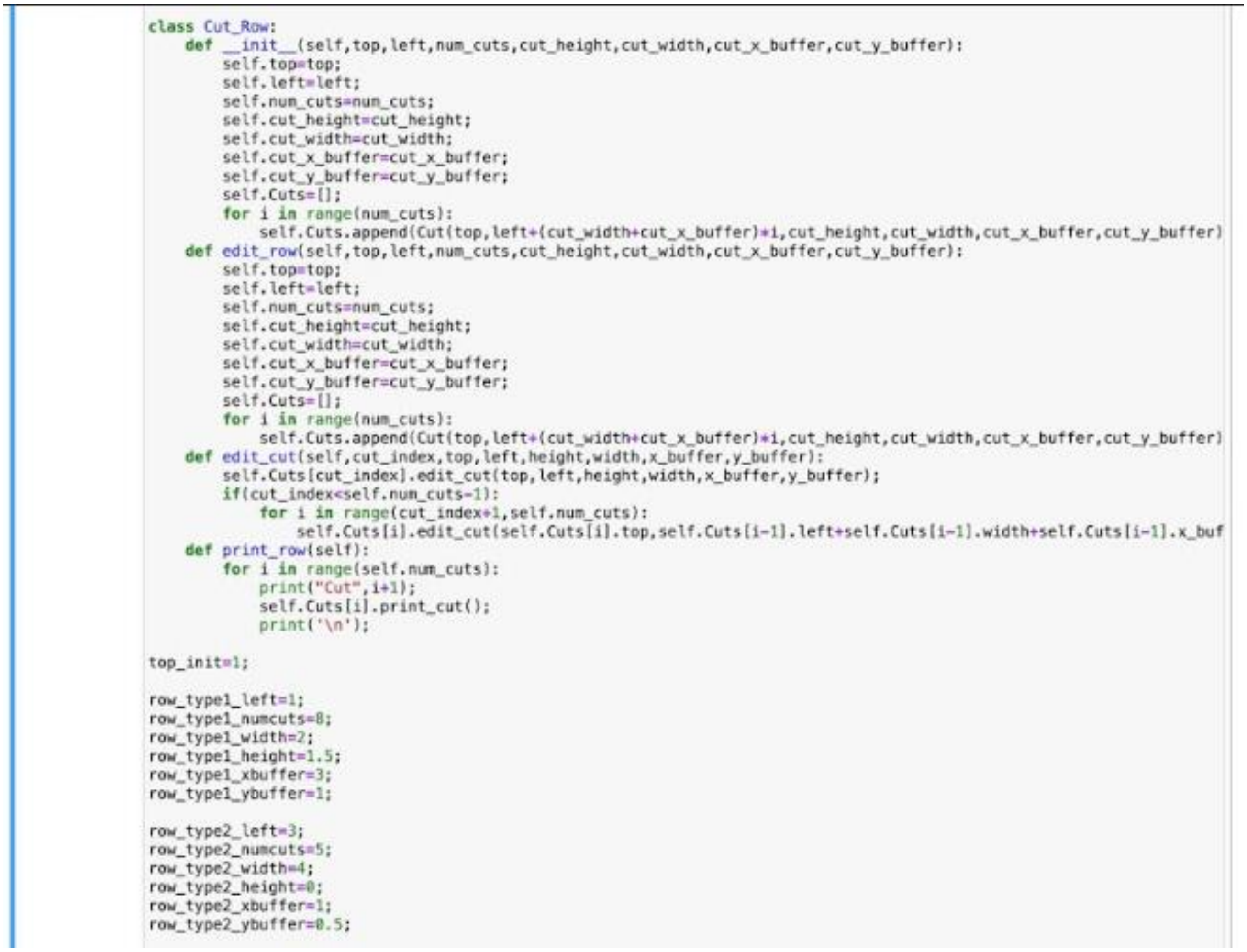
Substituting ΔW, β, and L_F and using $R_1 = {}^{L_C}\!/_{x}$ and $R_2 = {}^{L_C}\!/_{y}$ to non-dimensionalize, simplification of ε_T yields:

$$\varepsilon_T = \frac{R_1 - 1}{R_1 + 1}\left[\cos\left(\sin^{-1}\left(\frac{2R_1\tan\theta}{R_1R_2 - R_2}\right)\right) - 1\right] \tag{11}$$

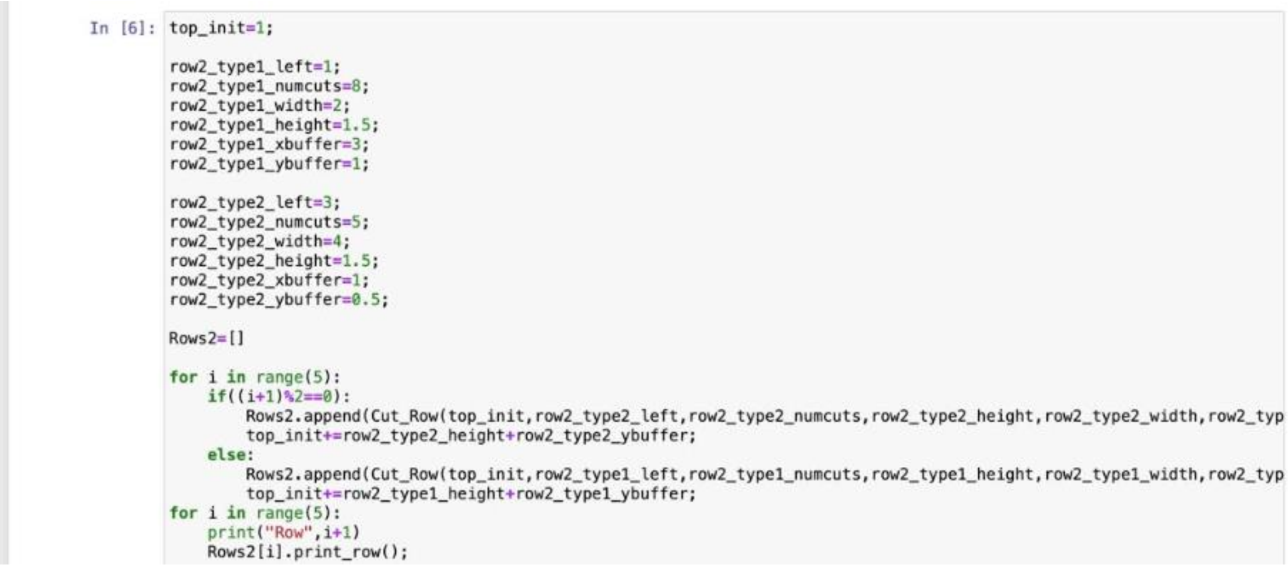
Supplement Note 2

Cuts Code Python 3 in Jupyter Notebook

```python
"""
@author: Sanika Barve
"""

class Cut:
    def __init__(self,top,left,height,width,x_buffer,y_buffer):
        self.top=top;
        self.left=left;
        self.height=height;
        self.width=width;
        self.x_buffer=x_buffer;
        self.y_buffer=y_buffer;
    def edit_cut(self,top,left,height,width,x_buffer,y_buffer):
        self.top=top;
        self.left=left;
        self.height=height;
        self.width=width;
        self.x_buffer=x_buffer;
        self.y_buffer=y_buffer;
    def print_cut(self):
        print("Top=",self.top,",Left=",self.left,",Height=",self.height,",Width=",self.width);
```

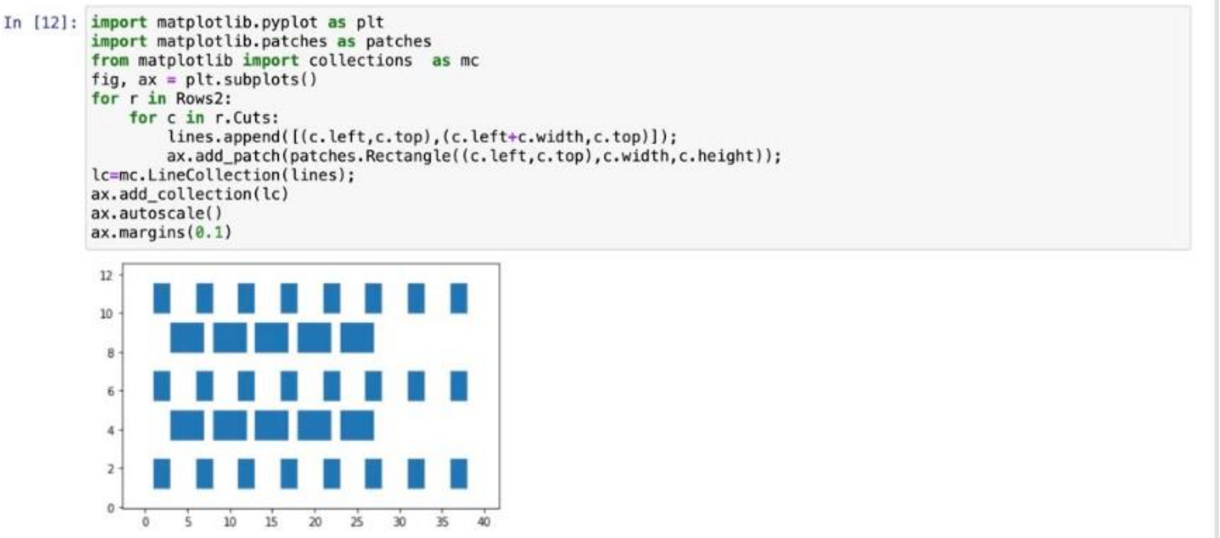


```
class Cut_Row:
    def __init__(self,top,left,num_cuts,cut_height,cut_width,cut_x_buffer,cut_y_buffer):
        self.top=top;
        self.left=left;
        self.num_cuts=num_cuts;
        self.cut_height=cut_height;
        self.cut_width=cut_width;
        self.cut_x_buffer=cut_x_buffer;
        self.cut_y_buffer=cut_y_buffer;
        self.Cuts=[];
        for i in range(num_cuts):
            self.Cuts.append(Cut(top,left+(cut_width+cut_x_buffer)*i,cut_height,cut_width,cut_x_buffer,cut_y_buffer)
    def edit_row(self,top,left,num_cuts,cut_height,cut_width,cut_x_buffer,cut_y_buffer):
        self.top=top;
        self.left=left;
        self.num_cuts=num_cuts;
        self.cut_height=cut_height;
        self.cut_width=cut_width;
        self.cut_x_buffer=cut_x_buffer;
        self.cut_y_buffer=cut_y_buffer;
        self.Cuts=[];
        for i in range(num_cuts):
            self.Cuts.append(Cut(top,left+(cut_width+cut_x_buffer)*i,cut_height,cut_width,cut_x_buffer,cut_y_buffer)
    def edit_cut(self,cut_index,top,left,height,width,x_buffer,y_buffer):
        self.Cuts[cut_index].edit_cut(top,left,height,width,x_buffer,y_buffer);
        if(cut_index<self.num_cuts-1):
            for i in range(cut_index+1,self.num_cuts):
                self.Cuts[i].edit_cut(self.Cuts[i].top,self.Cuts[i-1].left+self.Cuts[i-1].width+self.Cuts[i-1].x_buf
    def print_row(self):
        for i in range(self.num_cuts):
            print("Cut",i+1);
            self.Cuts[i].print_cut();
            print('\n');

top_init=1;

row_type1_left=1;
row_type1_numcuts=8;
row_type1_width=2;
row_type1_height=1.5;
row_type1_xbuffer=3;
row_type1_ybuffer=1;

row_type2_left=3;
row_type2_numcuts=5;
row_type2_width=4;
row_type2_height=0;
row_type2_xbuffer=1;
row_type2_ybuffer=0.5;
```

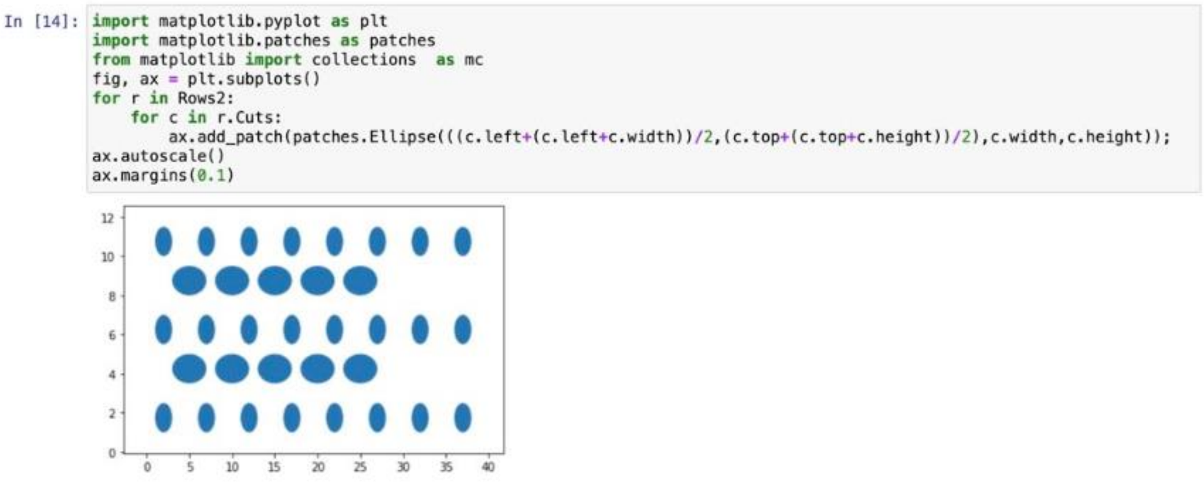


```
top_init=1;

row2_type1_left=1;
row2_type1_numcuts=8;
row2_type1_width=2;
row2_type1_height=1.5;
row2_type1_xbuffer=3;
row2_type1_ybuffer=1;

row2_type2_left=3;
row2_type2_numcuts=5;
row2_type2_width=4;
row2_type2_height=1.5;
row2_type2_xbuffer=1;
row2_type2_ybuffer=0.5;

Rows2=[]

for i in range(5):
    if((i+1)%2==0):
        Rows2.append(Cut_Row(top_init,row2_type2_left,row2_type2_numcuts,row2_type2_height,row2_type2_width,row2_typ
        top_init+=row2_type2_height+row2_type2_ybuffer;
    else:
        Rows2.append(Cut_Row(top_init,row2_type1_left,row2_type1_numcuts,row2_type1_height,row2_type1_width,row2_typ
        top_init+=row2_type1_height+row2_type1_ybuffer;
for i in range(5):
    print("Row",i+1)
    Rows2[i].print_row();
```

```
In [4]: import matplotlib.pyplot as plt
        import matplotlib.patches as patches
        from matplotlib import collections  as mc
        lines=[]
        fig, ax = plt.subplots()
        for r in Rows:
            for c in r.Cuts:
                lines.append([(c.left,c.top),(c.left+c.width,c.top)]);
                ax.add_patch(patches.Rectangle((c.left,c.top),c.width,c.height));
        lc=mc.LineCollection(lines);
        ax.add_collection(lc)
        ax.autoscale()
        ax.margins(0.1)
```



```
In [12]: import matplotlib.pyplot as plt
         import matplotlib.patches as patches
         from matplotlib import collections  as mc
         fig, ax = plt.subplots()
         for r in Rows2:
             for c in r.Cuts:
                 lines.append([(c.left,c.top),(c.left+c.width,c.top)]);
                 ax.add_patch(patches.Rectangle((c.left,c.top),c.width,c.height));
         lc=mc.LineCollection(lines);
         ax.add_collection(lc)
         ax.autoscale()
         ax.margins(0.1)
```



```
In [14]: import matplotlib.pyplot as plt
         import matplotlib.patches as patches
         from matplotlib import collections  as mc
         fig, ax = plt.subplots()
         for r in Rows2:
             for c in r.Cuts:
                 ax.add_patch(patches.Ellipse(((c.left+(c.left+c.width))/2,(c.top+(c.top+c.height))/2),c.width,c.height));
         ax.autoscale()
         ax.margins(0.1)
```

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