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INTEGRATING PIEZOELECTRIC ACTUATORS ONTO KIRIGAMI MATRICES TO INFLUENCE THEIR DEPLOYMENT

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ABSTRACT

The ability to influence the deployment of multi-stable kirigami matrices opens up the possibility to create variable stiffness structures. This research paper explores the design of a test jig built to assess the integration of piezoelectric actuators onto kirigami matrices. The jig provides a controlled environment in which the effects of the piezoelectric components can be distinguished, and as such observed independently. The test setup consists of a piezo control circuit, boosting voltages of 5 V to 12 V up to 390 V and 780 V respectively, allowing for a maximum deflection of the piezo actuators of 0.9 mm. A pair of rail-mounted clamps ensure the kirigami sheets are deflected uni-axially, all while enforcing a uniform load across their span. Although both the piezo driving circuit and kirigami sheet loading jig worked as expected individually, several unexplored factors led to unfavourable results once both modules were combined together. Despite the inconclusive nature of the experiment, the existence of noticeable deflections on the kirigami sheets driven by the piezoelectric components leads to the belief that an increase in the number of piezo components on the sheet accompanied by a redesign of the kirigami sheets would yield promising results.

Keywords: Kirigami, Piezoelectrics, Actuation

1 INTRODUCTION

Both origami and kirigami have been receiving growing attention in recent years, most notably due to their ability to transform large flat sheets into more compact folded counterparts [1]. Kirigami, allowing both cuts and folds, has however not been as deeply explored as origami, and many structural applications of this ancient art are still being discovered to this day [2]. The response of kirigami lattices to external forces allows for complex three-dimensional shapes to emerge from two-dimensional sheets, with the help of well placed cuts, allowing for the creation of actuators [3] or even multi-stable structures [4]. These have notably been used for medical applications, such as the creation of soft grippers [2] or sustained localised drug delivery systems [5], however they find their place in engineering as well, allowing for integrated solar tracking [6] or efficient soft body crawlers [7].

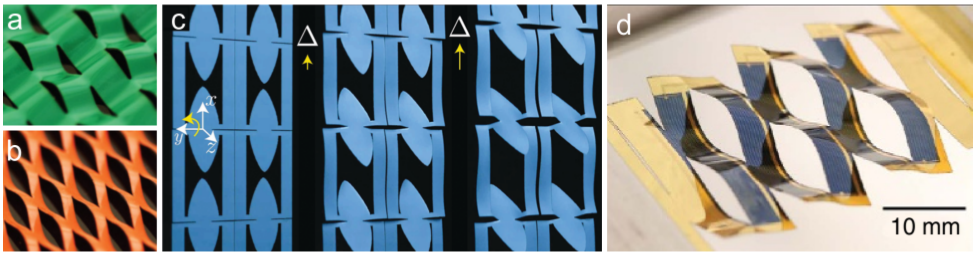


Figure 1: Kirigami lattice examples and uses. a) Asymmetrically deployed kirigami structure [4] b) Symmetrically deployed kirigami structure [4] c) Rotating kirigami actuator [3] d) Kirigami pattern in use for solar tracking [6].

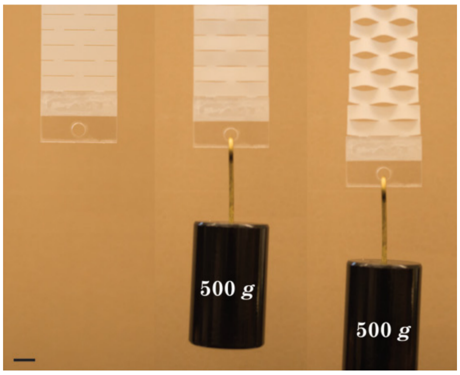


Figure 2: Tuning stiffness of multi-stable kirigami to lift 500g weight [4].

Kirigami lattices are currently produced with a single deployment geometry in mind. Cut matrices are designed to allow for a set range of motion under load, with the only control over the kirigami sheets being from the tensile or compressive force applied to them. For a different deployed state to be achieved, a change in the cut matrix must have occurred. Despite this, multi-stable kirigami lattices have been developed [4], and allow for the matrices to be shifted between two different states. The unit cells of the kirigami matrix switch between a symmetric and asymmetric state (see Figure 1.a,b), providing higher rigidity or flexibility respectively [4]. Due to this, the resistance of the sheet to load can be tuned, as illustrated in Figure 2. To change a cell's state, an external load is necessary, either once the kirigami is loaded, or to act as a bias prior to loading the sheets. By integrating a means to dynamically affect the deployment of each cell, either by integrating flexible actuators or making use of modal nudging [8], this behaviour can be harnessed to create variable stiffness springs, for example. Despite this possibility to control these lattices deployment externally, there has not yet been any research surrounding self-contained kirigami actuation.

For typical kirigami matrices however, the only method of actuation lies in varying the tensile or compressive force applied to the kirigami sheets, as seen in the integrated solar tracking array [6]. Despite this, an effort has been made to create more advanced kirigami actuators, which transform tensile load into a variety rotations and translations, most notably pitch, yaw, roll and lift [3]. Kirigami could become a very important tool to lightweight structures if given the possibility to actively control its state using integrated methods. Furthermore, research has been lead on the deployment pattern of cylindrical kirigami skins [9]. As opposed to flat sheets, cylindrical kirigami elements pop-out locally at imperfections, before propagating throughout the entire shell; a useful characteristic that could be exploited for tuned kirigami deployment.

Although piezoelectrics have not been used to control kirigami matrix deployment, wearable piezoelectrics inspired by kirigami methods have been made [10]. These most notably provide a means to produce energy for portable devices, harvesting the energy created when deforming the lattices [11]. The success of these deformable piezoelectrics proves promising for the implementation of such techniques into kirigami structures, as they would necessitate bendable piezoelectrics to allow them to be controlled internally.

2 AIMS AND OBJECTIVES

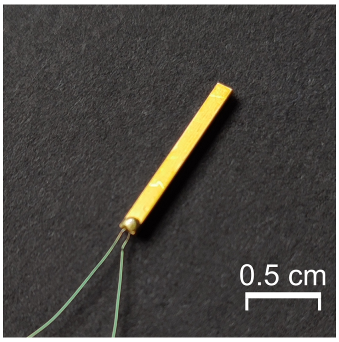
The aim of this project is to explore the integration of piezoelectric actuators onto kirigami sheets, to provide a means to control their deployment. By varying the state of each cell of the loaded matrix, it is possible to change the stiffness of the overall structure, hence the integration of piezoelectric would allow for a way to control the stiffness of the deployed kirigami structures. To deconstruct this aim into measurable targets, the following objectives have been put in place:

- To design a piezo driving circuit, allowing for a versatile range of deflection of the piezo actuators.
- To produce a testing jig applying uniform uni-axial loading to the kirigami sheets.
- To integrate the piezo actuators seamlessly onto the kirigami sheets, in such a way as to not impede of the matrices' deployment, but still allow for control over it.

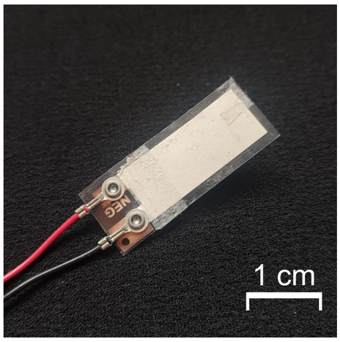
3 PIEZO ACTUATING CIRCUIT

In order to provide an accurate and repeatable method for assessing the effects of piezoelectric actuators on kirigami matrices, it is crucial to have a robust method for powering these components. The sustained high voltage necessary to obtain a useful deflection from the piezoelectric components leads to the need to design and produce a custom power supply. This circuit must be able to deliver voltage in the range of 200–1000 V, in order to control the amplitude of deflection of the piezo actuators effectively.

In addition to this, a suitable piezoelectric actuator must be chosen to ensure its integration onto the kirigami sheets does not limit their deployment. The two piezo actuators available for this project, displayed in Figure 3, show differing characteristics. The first piezo element, while being notably smaller, is rigid and does not deflect when under the test load of 1000 V. Due to this, it creates a localised defect on the kirigami sheets when integrated, causing unwanted deformation to occur once the sheets are loaded. More importantly, the lack of deflection under electrical load makes it unsuitable to be used as a control surface for this project. On the other hand, the second piezo element is flexible and deflects significantly when subject to a load of 1000 V, and is the component that is used throughout this research. Its large footprint is not ideal, as this will impede on the design of the kirigami sheets, but this is unavoidable given the selection of available piezo components.



(a)



(b)

Figure 3: Piezoelectric actuator selection. a) Piezo component 1 b) Piezo component 2.

The piezo driving circuit is designed to provide a simple, versatile and accurate power source for the piezoelectric actuators. It is built around a commercial off-the-shelf voltage booster, purchased for this project. The power deliverance is controlled by a three-way switch, allowing for the high voltage to be fed in either polarity to the piezo elements. As the switching speed is not crucial for this project, this polarity switch is achieved via the use of two relay bridges, which also serve as a means to insulate the high voltage lines from the lower input voltage lines. Each pair of relays making up the two bridges are controlled by a MOSFET, to greatly simplify the design of the circuit. When the control switch is in either on position, the associated MOSFET will power a pair of relays, connecting one side of the output terminals to ground, and the other to the high voltage source. These connections will shift when the control switch is in the other on position, resulting in the voltage polarity control. To ensure the circuit is safe, it is placed in a sealed acrylic box with a safety interlock, and contains a set of bleed resistors to rid of any excess power produced by the voltage booster.

The circuit and labelled components of the circuit are presented in Figure 4 below, alongside a circuit schematic in Figure 7.

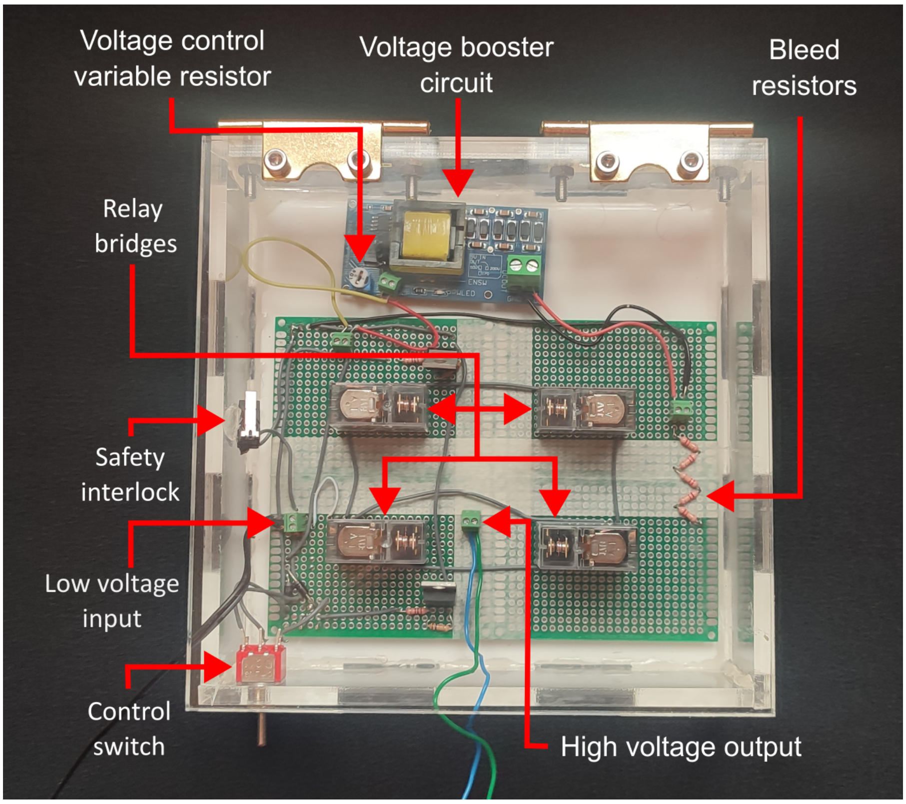


Figure 4: Piezo driving circuit.

To assess the performance of the designed and built circuit, measurements of the output voltage are taken for a range of power demand settings (0 % to 100 %), with varying input voltages (5 V, 9 V and 12 V). The achieved output voltages for each setting are presented in Figure 5 below.

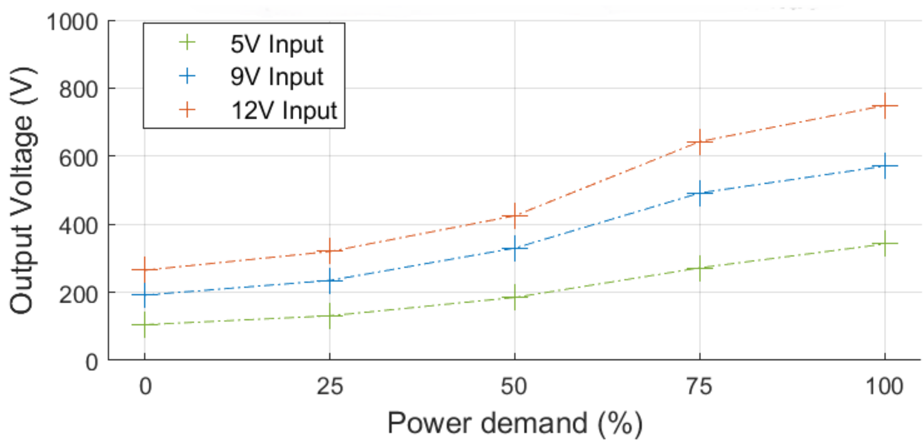
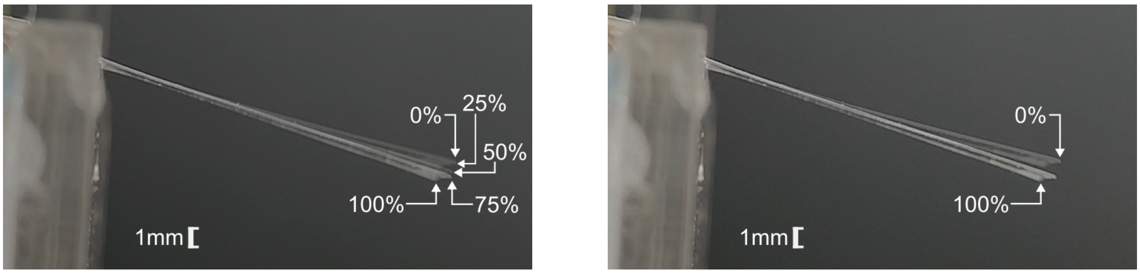


Figure 5: Output voltage at different power demands.

It can thus be determined that to achieve the largest range of output voltages, it is recommended to use a 12 V input voltage. This also allows for the highest overall output voltage, at a power demand of 100 %.

Using an input voltage of 12 V, the deflection of the piezoelectric actuator is assessed for different power demands, ranging from 0 % to 100 %. The deflection associated for each power setting is illustrated in Figure 6 below, with a maximum deflection of 0.9 mm at a power setting of 100 %.



(a) (b)

Figure 6: Deflection of the piezo element at different power demands, with a 12 V input. a) Deflection at each power setting b) Deflection at 0 % and 100 %.

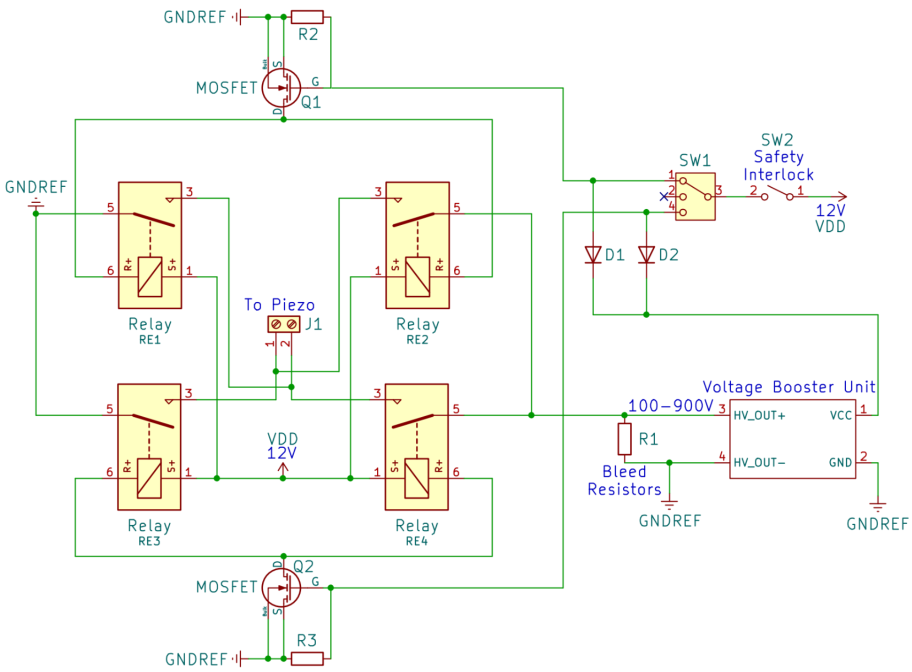
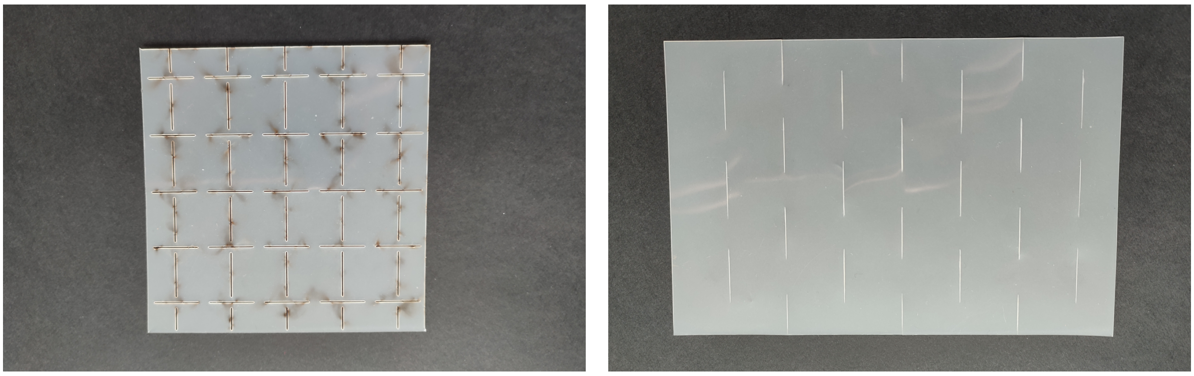


Figure 7: Piezo actuating circuit diagram.

4 KIRIGAMI LATTICES

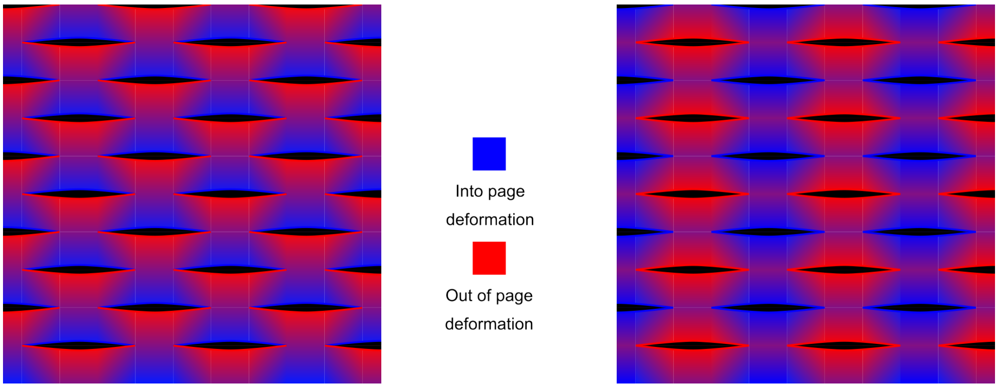
The kirigami lattices were cut out on mylar sheets of varying thicknesses (0.125 mm, 0.050 mm and 0.023 mm). Although these lattices can be cut using a CNC knife, a laser cutter is used in this project as the thinner mylar would wrinkle in the CNC knife, resulting in a failed cut. Before producing the matrices that will accommodate the piezoelectric components, test sheets are made to identify which cut pattern is the most suited to be actuated. A buckling induced kirigami pattern [12] was trialed first, as can be seen in Figure 8.a. It however require a large force to deform, and only deflected into a single state. As such, kirigami sheet produced using the data presented in *"Multistable kirigami for tunable architected materials"* [4] was assessed next, as can be seen in Figure 8.b, and was ultimately adopted for this research. These matrices deform under little load, and can be easily adapted for this research project.



(a) (b)

Figure 8: Example of trial matrices. a) Buckling matrix b) Multi-stable matrix.

Depending on the matrix cut parameters, these kirigami sheets deform into two distinct states: a stiffer symmetric state, or a more flexible asymmetric state, as illustrated in the height map in Figure 9 below. The cut parameters are defined in Figure 10, with Lx and Ly being the horizontal and vertical distance between cuts respectively, and Lc being the length of the cuts. [4]



(a) (b)

Figure 9: a) Asymmetric deployment deformation b) Symmetric deployment deformation.

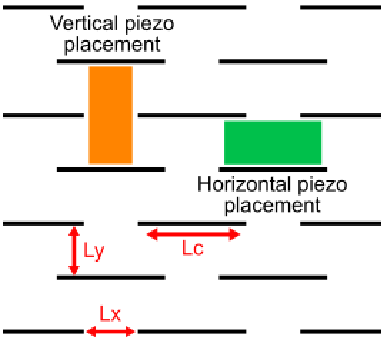
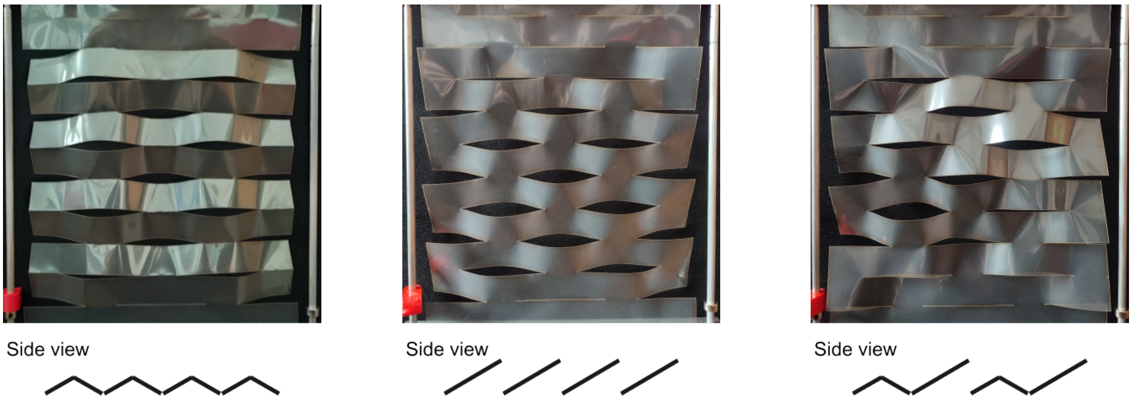


Figure 10: Cut settings and piezo placements.

This cut pattern can also be multi-stable when given the correct parameters [4]. Once deflected, each cell of a multi-stable kirigami sheet assumes either a symmetric or asymmetric state depending on minute defects or perturbations in the kirigami sheet prior to loading. This is a very favourable behaviour for this research, as these perturbations can be created by the piezoelectric actuators, allowing these to control the deployment of individual cells into a specific state. As the symmetric state displays higher stiffness than the asymmetric state, it is thus also possible to actively control the stiffness of the kirigami structure thanks to these piezo elements [4].

A multi-stable kirigami pattern designed to fit the selected piezo actuators is designed, with Lx and Ly both being set to 2.0 cm, and Lc being set to 6.4 cm. This allows for the piezos to be installed both horizontally or vertically between the cuts in the matrix, as can be seen in Figure 10. This matrix pattern can be seen in Figure 11, being deployed in its symmetric, asymmetric and chaotic state.



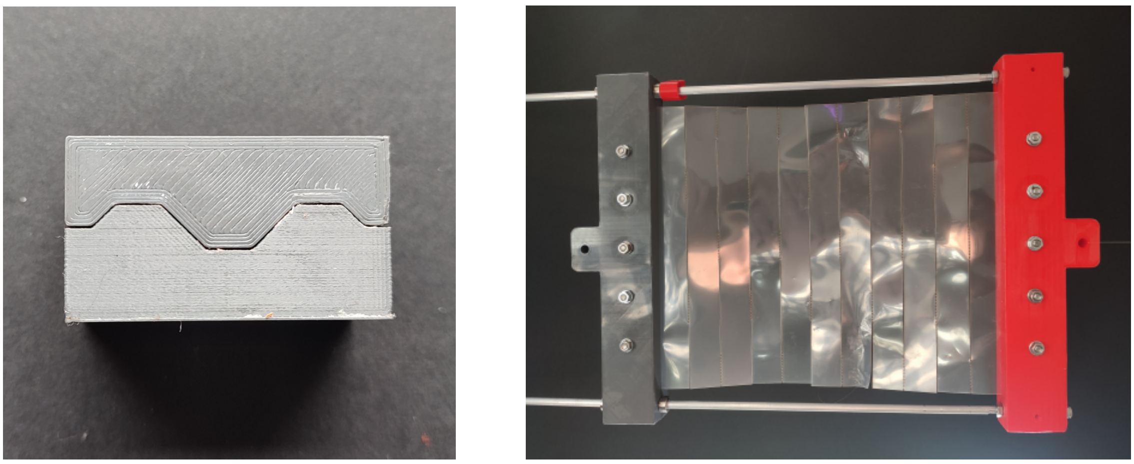
(a) (b) (c)

Figure 11: a) Symmetric deployment b) Asymmetric deployment c) Chaotic deployment.

5 KIRIGAMI SHEETS' BOUNDARY CONDITIONS

To ensure the effects of the piezoelectric actuators are correctly assessed, the kirigami sheets must be subjected to the correct boundary conditions. As any minor defect affect the deformation of these matrices, they must be displaced uni-axially, and from a distributed load.

When loaded, the multi-stable kirigami sheets are clamped at each end by a pair of 3D-printed blocks, with a jagged profile, as can be seen in Figure 12.a. The geometry of the clamps allows for the deformation load to be distributed uniformly across the width of the sheet. The blocks are bolted together along their span, to further ensure this, and ride along a pair of parallel rods, only allowing the sheet to subjected to a uni-axial tensile load. The full clamp and rail set up is presented in Figure 12.b.

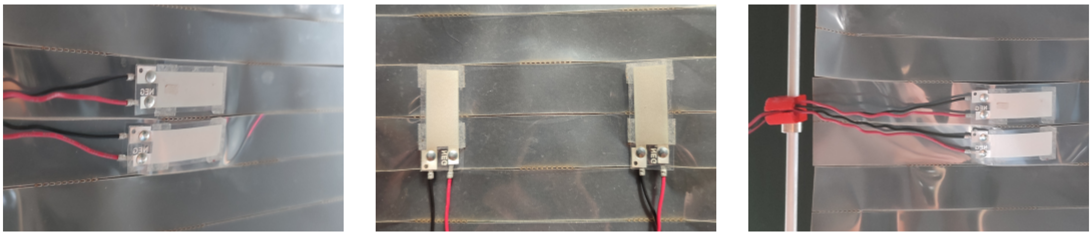


(a) (b)

Figure 12: a) Side view of clamp geometry b) Clamp setup.

6 INTEGRATING PIEZOELECTRICS ONTO KIRIGAMI LATTICES

In order to control the kirigami sheet's deformation, two piezoelectric actuators are attached to it with double sided mesh tape. They are placed both vertically and horizontally between the cuts in the sheet, as can be seen in Figure 10 and Figure 13.a,b. The components are positioned centrally on the kirigami matrix, to distance them from the free edges of the sheet. Furthermore, placing the piezo actuators on either side of the sheet would create a localised asymmetric defect which would in turn skew the results of the experiment.



(a) (b) (c)

Figure 13: a) Horizontal piezo positioning b) Vertical piezo positioning c) Wire clamp setup.

The piezo actuators serve as a means to control the deformation of the kirigami sheet once it is loaded. As the matrix designed for this research has a slight tendency to deploy asymmetrically, the aim of this experiment is to assess whether the integration of piezo actuators can push this matrix to deploy predominantly asymmetrically when the piezo elements are unpowered, and symmetrically when a current runs through them, as can be seen in Figure 14.

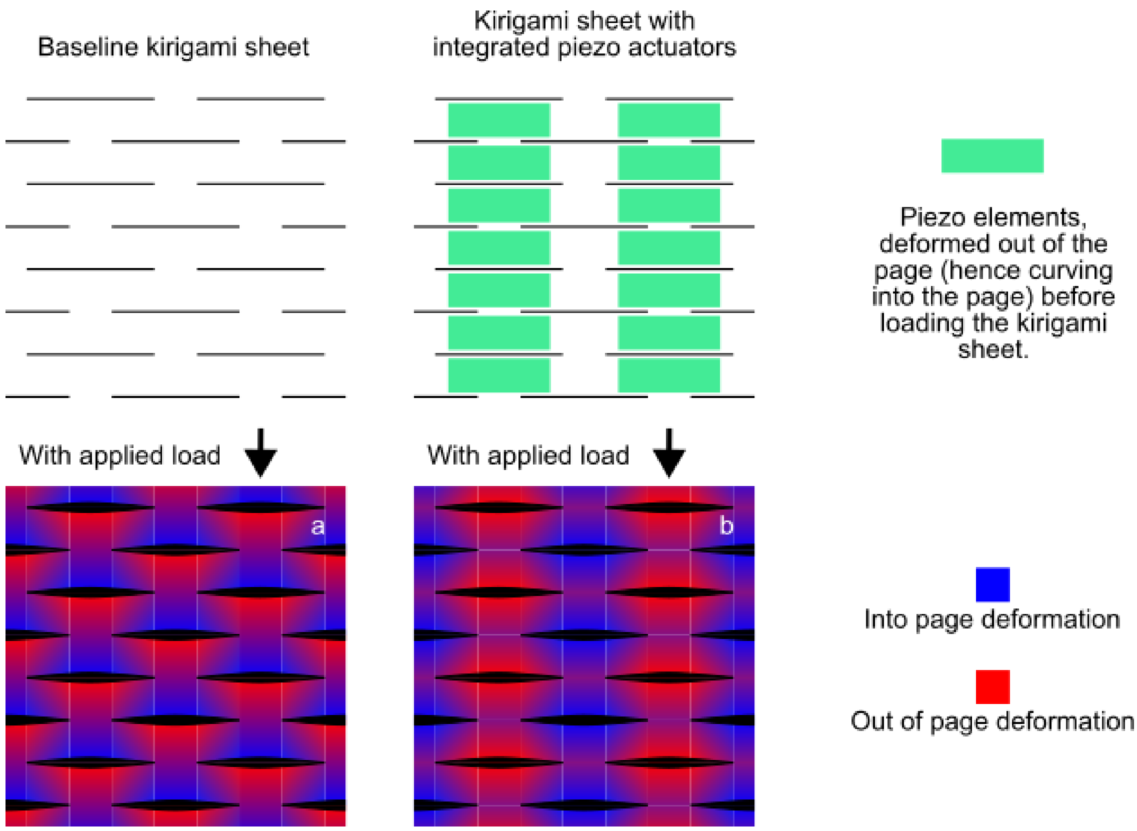


Figure 14: a) Baseline kirigami deployment b) Kirigami deployment with piezo actuators.

To assess how the piezo actuators should be deformed in both their horizontal and vertical placements (see Figure 10) to achieve the desired deployment, a Wheatstone bridge is developed to collect the change in voltage driven by the deflection of the piezo components. The more the piezo actuators are deformed, the higher the change in voltage occurs. The collected voltages are presented in Table 1 below, for both symmetric and asymmetric deployment, alongside a baseline value.

Table 1: Deflection amplitude at horizontal and vertical piezo placement.

Kirigami deflection	Wheatstone bridge voltage horizontal piezo placement	Wheatstone bridge voltage vertical piezo placement
No deflection	0.53 V (–)	0.57 V (–)
Symmetric deflection	1.11 V (+109 %)	0.93 V (+63 %)
Asymmetric deflection	1.65 V (+211 %)	0.64 V (+12 %)

As seen in Table 1, the vertical piezo placement yields lower voltage changes for both symmetric and asymmetric deflections than the horizontal piezo placement. Although the Wheatstone bridge allows for a comparison of the amplitudes of deflection at each piezo position, it is unable to illustrate the direction of deflection of each piezo component. With the piezo setup used for this research, displayed in Figure 13, two piezo elements positioned vertically will deflect in the same direction whether the matrix is deployed symmetrically or asymmetrically, while two piezo elements positioned horizontally will only deflect in the same direction when the matrix is deployed symmetrically. Given the larger deflection values and variability in necessary deflection direction for the horizontal piezo position, it is the most likely to affect the kirigami sheet's deployment once integrated.

Across each test, the kirigami sheet was loaded with a 15 mm deflection, which allowed for observable deformation of each cell. As the unsupported wires of the piezos perturbed the deployment of the matrices, a wire clamp was added to one of the guide rods, to hold them out of the way during testing, as can be seen in Figure 13.c. For each thickness of mylar, the kirigami matrix was loaded without any piezo drivers attached, with the piezos attached but unpowered, and finally with the piezos both attached and powered prior to and during loading of the sheet.

Despite running the piezos at the maximum voltage the driving circuit can produce, they did not affect the kirigami sheets. The piezo drivers could only slightly bend the thinnest unloaded mylar sheet, which was not enough to push it to deploy symmetrically once loaded, and led to the kirigami sheets deploying asymmetrically for every test.

7 DISCUSSION

7.1 Piezo actuating circuit

As designed, the circuit provided an accurate power source for the piezo actuators. Despite the use of relays, the polarity switching was quick and allowed for the actuators to be deformed in either direction, increasing its usability. Although the circuit was tested by powering a single piezo component, it functioned just as well when powering the two actuators used in the final experiment simultaneously.

7.2 Kirigami sheets

Although laser cutting kirigami matrices out of mylar was quite novel, the method proved very reliable, and allowed for very fine mylar to be used. The resulting sheets were without defect, and behaved as expected once cut. Among the three thicknesses of mylar used in this research, the thinnest offered the best results. Having lower bending coupling, the multi-stable kirigami sheet cut out from this mylar displayed the most chaotic deployment. Each cell was less affected by their neighbour's displacement, and deformed purely based on initial imperfections. On the other hand, the multi-stable matrix cut from the thicker mylar sheet tended to deploy fully symmetrically or asymmetrically.

Limitations on availability meant the largest mylar sheet accessible were quite small, with a dimension of 30.4x20.0 cm. When considering the space necessary to fit the piezo actuators, this lead to very cramped kirigami matrices. The low number of cells per sheet meant each cell was greatly affected by its neighbouring cells, and by the free edges of the sheet, as more material connected them. This matrix tended to deflect fully asymmetrically due to this, despite being designed as multi-stable.

Nonetheless, the jagged clamp system helped uniformly distribute the deflection load and mitigate this effect. The 3D-printed blocks were quite heavy, which meant that it was not possible to vary the load applied on the kirigami sheets, at the weight of the blocks alone would deform them fully.

7.3 Integration of piezo actuators onto kirigami sheets

Unfortunately, the piezoelectric actuators cannot be said to have affected the deployment of the kirigami lattices. These components did not deflect enough to reliably vary the state of the multi-stable matrix in the configuration tested in this research. When unloaded, only the thinnest mylar showed any signs of deformation caused by the piezo actuators.

Multiple factors made it difficult to collect any conclusive results. By sticking the piezo components onto the mylar, it created a localised increase in thickness and as such a defect in the lattice, affecting the deployment of the kirigami. Furthermore, although a wire clamp had been installed onto the testing bed, these still provided slight lateral resistance when the sheets were loaded, skewing the results of those tests.

Ideally, a larger kirigami sheet would be utilised, in such a way to have a larger number of piezo actuators integrated onto the matrix. The increased distribution of actuators would create a more uniform matrix, as the added thickness introduced by the piezos would be spread across each cell, instead of being localised at a single point on the matrix. To improve even further on the design, a kirigami could be produced out of piezoelectric material, as these are mainly made of mylar. This would result in a sheet of even thickness, and would allow for integrated wiring, nullifying the issues mentioned prior.

8 CONCLUSION

In this paper, a test bed to evaluate the integration of piezoelectric actuators onto kirigami sheets to control their deployment was developed. A high voltage piezo driving circuit was designed and built to offer a precise method for deflecting the piezo components, and hence preload the kirigami matrices. Specially designed lattices were conceived in order to accommodate the piezo actuators. A clamp system was mounted on guide rails to uniformly load the kirigami sheets and provide a uni-axial deformation, enforcing the necessary boundary conditions, and ensuring repeatable and comparable testing of every configuration of the matrices.

Despite the success of the individual components of the test setup, the results were unfortunately inconclusive. Many unexpected disturbances delayed the collection of results, and led to difficulties proving the feasibility of this project. As such, it cannot be said that the piezo actuators offer a means to control the deployment of the kirigami sheets in the conditions they have been tested in for this research. Nonetheless, the development of a versatile power source and precise loading clamps will allow for further research to be conducted on the subject, with an improved understanding of the precautions to take to ensure viable results.

9 RECOMMENDATIONS AND FUTURE WORKS

9.1 Recommendations

If further research is to be carried out on this subject, it should aim to test the integration of piezo actuators on bigger mylar sheets, to avoid the interaction of their free edges on the deployment of the matrix. This allows for the piezo actuators to have a larger influence on the deformation of each cell of the lattice, all while leaving more space for a large number of piezo elements. Additionally, increasing the coverage of the piezo components would further improve their control on the deployment of the matrix, as each cell is influenced by the deformation of its neighbouring cells.

It is also recommended to use thinner mylar sheets, in the range of 0.023 mm, as a lower coupling between cells of the kirigami sheets will ensue, making the piezo elements more influential on the deployment of the cell they are attached to.

Using piezo actuators that deflect more significantly than the ones used in this research paper would also aide in obtaining favourable results. Currently, the maximum deflection of 0.9 mm of the piezo drivers used is not sufficient to impact the deployment of the kirigami matrices.

9.2 Future Works

In future works, focus should be set on improving the integration of the piezo actuators onto the kirigami lattices. The current piezo driving circuit and kirigami clamp setup work as designed, and do not need any improvements. This in itself would streamline any further research on the subject.

To increase the likelihood of success, it would favourable to produce a larger kirigami matrix out of piezoelectric material. As such, the deformation produced by the piezo actuators could be tailored to reliably control the state of a multi-stable matrix once loaded, and would allow for a denser distribution of piezo actuators across the sheet. Furthermore, this would result in kirigami sheet of uniform thickness, eliminating localised defects, as are produced with the current method of piezo integration.

Integrating the actuators into the kirigami sheets in this manner would also reduce the impact of the piezo's wires on the deployment of the matrix. Although this interference was mostly eliminated by the introduction of a wire clamp in this project, it would be advantageous to remove their presence overall.

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