MECHXELS: LEVERAGING BISTABLE STRUCTURES FOR COLOR CHANGE, CHARACTER, AND IMAGE DISPLAY

by

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ABSTRACT

A key aspect of color change is altering perceived value or intensity. This dissertation presents a methodology to achieve value change through mechanical means via the deflection of bistable structures. We create the Mechxel, two methods of mechanical pixel-based, reversible color change using 3D printed switchable multistability and bistable switch panels that augment the projected area a viewer perceives which enables the creation of image and character tessellation.

Switchable multistability (SMS) arises from the combination of pre-strain and shape memory, allowing us to access multiple elastically programmed shapes at elevated temperatures with fast morphing and low actuation forces, while retaining high stiffness at room temperature. We design and manufacture SMS Mechxels using fused deposition modeling (FDM) 3D printing on the Ultimaker 3D printer in a bilayer layup of polylactic acid (PLA) with a [90/0] print direction while iteratively miniaturizing the physical size to enhance the resolution while also reducing the size of the overall tessellated display. Leveraging SMS properties programmed into each Mechxel, the projected area to a viewer will vary between the unit's stable states, creating a difference in perceived value of coloration due to changes in area. To ease the tessellation process, we also introduce a tessellation user interface that maps images to their tessellated equivalent to reduce tessellation trial and error. This interface also calculates the number of Mechxels required in their respective states and the final physical size of the display. We then carry out image processing to justify this change in value between stable states and run preliminary optical character recognition.

Inspired by mechanical bistable mechanisms, the bistable switch Mechxels utilize changes in a surface's projected area to a viewer via changes in the angle of a bistable tile using a 5-by-5 grid for character replication and display. Comprising of three main components – two bistable switches, a colored tile and a base, design considerations were made to create an easy to assemble and replaceable 3D printed grid system that could be interacted with by audiences or easily electromechanically actuated. Using pixel-by-pixel comparisons and Sorensen-Dice coefficient, characters using the typeface Silkscreen were documented on these tiled grids yielding high similarity and low error when compared to their digital reference images in various positions and orientations. We also experiment with transitional waves as a promising means of actuation to change the Mechxel between their stable states.

The Mechxels considered in this research introduce a new means of purely mechanical color change, character, and image display either leveraging the elastic properties of shape memory polymers (SMPs) or bistable mechanisms. With potential applications in passive morphing architecture, adaptive camouflage, and interactive aesthetic, Mechxels opens the door to limitless design possibilities through a new perspective into color change.

1. INTRODUCTION

Multistable structures and mechanisms are those that have two or more stable equilibrium states, resulting in structural property variations that can be tailored for various applications. Within the area of such structures, Switchable Multistable Structures (SMS) [1] have large potential applications due to the low cost, repeatability and reversibility which is independent of material system or actuation method. Such structures can change between equilibrium states when subjected to external stimulus or actuation inputs, such as temperature change or external forces. Although potential for such multistable structures is vast and have seen promise in the fields of aerospace, robotics and various biomedical devices, their potential has not been explored in innovative applications such as uses in display and color change technology for functional or aesthetic purposes. Consequently, this research explores novel approaches for the application of SMS and a general multistable mechanism for applications in the areas of color change and display technology.

1.1 State of the art

Natural color change serves many purposes, including mate attraction and active camouflage [2]. In most cases, this is achieved through the expansion and contraction of pigment sacs, called chromatophores, or a cephalopod's neuromuscular organs that operate in response to the environment without force activation [3,4]. These pigment sacs enable animals to create localized small changes in area of color to provide a constitutive visual change. Taking biological evolution as inspiration, numerous new technologies and research areas have emerged in the area of color change that leverage changes in perceived area of color to vary perceived color intensity [5]. These methods use actuation techniques such as stress-induced monodirectional color changing polymers [6,7], electrochemical mechanophores [5,8], reflective color display technology [9], as well as photochromatic dyes [10,11], thermochromic filaments, and specially manufactured polymers [12]. Bioinspired value change through varying surface texture has also been studied using stored elastic strains in origami-based structures [13].

Multistable structures have two or more stable equilibrium states, allowing the system to remain in either one of those states without external input. Bistable and multistable mechanisms have been proposed and applied across a varied number of fields with numerous techniques and materials to achieve desired stiffness variability [14,15], gripping capabilities [16] and novel applications such as tape springs [17] and switches [18], among others. Applications such as the shape morphing wings focus their design on the geometry of the structure using the curvature of an arch structure that is constrained at the two short edges, two stable states can be achieved which allows stiffness variation between their states [14,15]. Bistability and multistability can also be achieved through origami structures from facet bending [19] or crease extension [20], enabling the structure to achieve a snap-through capability not otherwise possible in flat sheet origami structures[16]. Other more familiar instances of bistability and multistability can be examined in the behavior of tape springs [21] and bilayer 4D shape changing printing [1] which capitalize on plastic deformation or direction pre-strain during the manufacturing process, respectively.

With advancements in Fused Deposition Modelling (FDM) and capabilities in 3D printing technology, the aforementioned multistability can readily be programmed into a model during manufacturing [1]. In this instance, multistability arises through a combination of the shape memory effect in materials such as polylactic acid (PLA) and directional pre-strain during FDM 3D printing [1,22], enabling fast, reversible and repeatable morphing that is not limited to any specific material system or actuation method. Usually, structures that are manufactured in this way are known for both their low actuation force, and high load-carrying capabilities. With the added ease of FDM 3D printing, they are also easy to manufacture and scale and can be designed and prototyped rapidly when design changes are necessary. This shape change not only results in adaptation of the physical structure, but also a variance in visual texture as the material deforms. With the addition of recoverable shape memory, varied functionality and aesthetic transformation can also be induced post manufacturing [1].

Perceived visual changes have also seen repute in numerous public sculptures and architectural installations. One such company that has gained public notice in the recent years is BREAKFAST [23], a new media artistic collective that creates works that are software and hardware driven to give audiences interactive experiences. They combine computer sciences, mechanical engineering, and aesthetics to create kinetic sculptures, such as the *Harvard Time Capsule* [24] and *Thread Screen* [25] which reflect either real-time or delayed images of audiences' interactions with the piece by using a flip-disc display or spools of colored thread. Both methods allow changes in the image produced through rotating surfaces, creating a binary color system, or color variations along lengths of material, such as the thread. Other notable artists who do similar works include Daniel Rozin [26], who uses everyday objects to create interactive “mirror” installations such as *Penguins Mirror* [27] (Figure 1.1a), and Christian Moeller, who used his carefully separated plates to line a building, allowing the shadow cast by the sun to create varying tonal values to display detailed images when viewed from afar [28]. The textural impact on a reproduced image can also be seen in Moeller’s work *dePictured (Bitwall 4)* [29] which utilizes horizontal slats to create images of inmates photographed in a German jail. Installations such as Christian Moeller’s *dePictured (Bitwall 4)* [29] and *Hands* [30] (Figure 1.1b) either leverage shadows cast by reliefs in the wall’s surface to create variations in value or contrast between negative space and white circular tiling respectively to allow images to be produced. Although the surface of the wall is a homogenous off-white color, by varying both the positioning and size of individual protrusions on the wall, light is either purposefully obstructed or directed into various areas which allow contrasts of light and dark values to delineate the stagnant image presented.

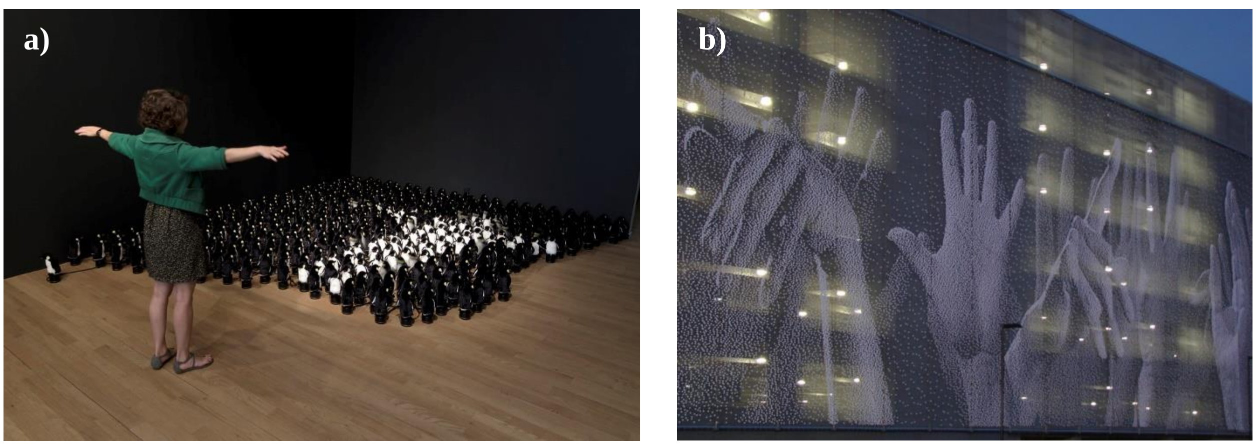

Figure 1.1. a) Reproduction of documented image of Daniel Rozin’s *Penguins Mirror* [27] with permissions from the Creative Commons License to create a real-time “reflection” of a viewer’s silhouette and b) Reproduction of documented image of Christian Moeller’s *Hands* [30] with permissions from the Creative Commons License.

1.2 Design Gap

Of the various color change methods, a challenged faced is that the structures designed to exhibit adaptive coloration using pigments is their dependence on specialized material systems customization of material being used. Research such as Photo-Chromeleon [11], metamoCrochet

[31] and Tricolor-changing Artificial Flowers [32] are characterized by their gradual change in hue [11] and require circuit calibration for stimulated actuation [12,31,32] or specialized material handling [12,32], which limits their accessibility. Furthermore, stress-induced monodirectional color changing polymers [6,7] do not have the ability to revert to their original color due to the change being linked to plastic deformation in their polymer structure. As such, they become both difficult to replicate and not functional for repurpose or reuse, most of the times seeing application to characterize issues within a designed structure.

Color change stemming from material deformation as demonstrated by COLORISE [33] and Bellieswave [34] require pneumatic actuation and large areas for a single "pixel". For the color change to be maintained, constant actuation is required. To meet these requirements, scaling the model becomes exponentially complex. These methods of perceived color change also require intensive construction techniques include understanding of coding algorithms that drive the system and each unit cell. Kinetic installations by BREAKFAST and Daniel Rozin are similar in that respect, where the collective or individual requires specialized help from experts in each field of controls and manufacturing and assembly to realize these pieces. In contrast, the inability to achieve the desired control system leads to the opposite occurrence. Installations such as the Marina Bay Sands *Wind Arbor* by Ned Kahn [35] and works by Daniel Rozin relinquish creator controllability entirely, allowing the installation to succumb to the environment or remain physically devoid of motion and interactivity.

Examination of contributions in the area of general morphing or multistable structures and color change can also be said to be isolated. Examples of research into morphing structures include hygroscopic shape change in wood veneers [36], wood fiber infused 3D printing filaments [37–39] or organic cellular structures [40] that enable novel applications architectural or wearable design respectively. In cases with wood materials, morphing occurs due to diffusive processes over the span of hours or days resulting in slow, subtle changes that may not be immediately observable. Investigation towards these types of 4D morphing structures have placed emphasis to change in physical form and response time but has yet to explore the visual impact that it creates due to such changes. On the other hand, multistable structures have been researched predominantly for the understanding of the fundamentals or tuned only particular applications. This includes characterization of its behaviour, structure, and geometry. However, with structural characterization and understanding, bistable structures have seen structural applications in areas of robotics [16,20,41,42], consumer products [21,43] and aerospace [14,15] among others but the visual impact of the bistable change in state has yet to be explored. Similarly, color change research continues to be focused in the fundamentals on a chemical level and not yet implemented in applications. Materials must be specially handled and manufactured with little emphasis on demonstrating purpose and application. As such, *there is an evident gap in leveraging structural methods for create perceived color change for both novel and practical applications*.

1.3 Contribution

Inspired by how cephalopods adapt their color through a variance in area of coloration at a cellular level, we present Mechxels in two alternative methods of passive deformation based color change that achieves macroscopic visual changes. With the primary focus on a change in value to result in a perceived difference in color, the first leverages switchable multistability and 4D printing [1] to create passive deformation-based value change, which is defined as a perceived variation in color intensity: the lightness or darkness of a color (Figure 1.2a). This enables a purely elastic form of color change without the need for special handle or manufacturing of materials. Capitalizing further on the fundamentals of perception and projected area to the viewer, the other method utilizes bistable structures to augment the angle of individual cells enabling variation in the perceived area of coloration to achieve a similar change in perceive color intensity (Figure 1.2b).

These designs are then manufactured using accessible FDM 3D printing and assembled by hand within a matter of hours. With our systematic method for mapping an image to its Mechxel tessellation equivalent, we are then able to readily replicate the production of images and text with limited trial and error, while calculating the physical dimensions of the tessellation and number of Mechxels required. This process culminates in a simple interactive demonstrator that is easy to maintain and interact with. Additional preliminary investigation into practical actuation methods, user interaction and image and text recognition are also explored. Ultimately, Mechxel's deformation-based value change enables exciting new possibilities for image and text display and points to unexplored potential in the areas of architecture, camouflage and art and design by viewing current research through a different design lens.

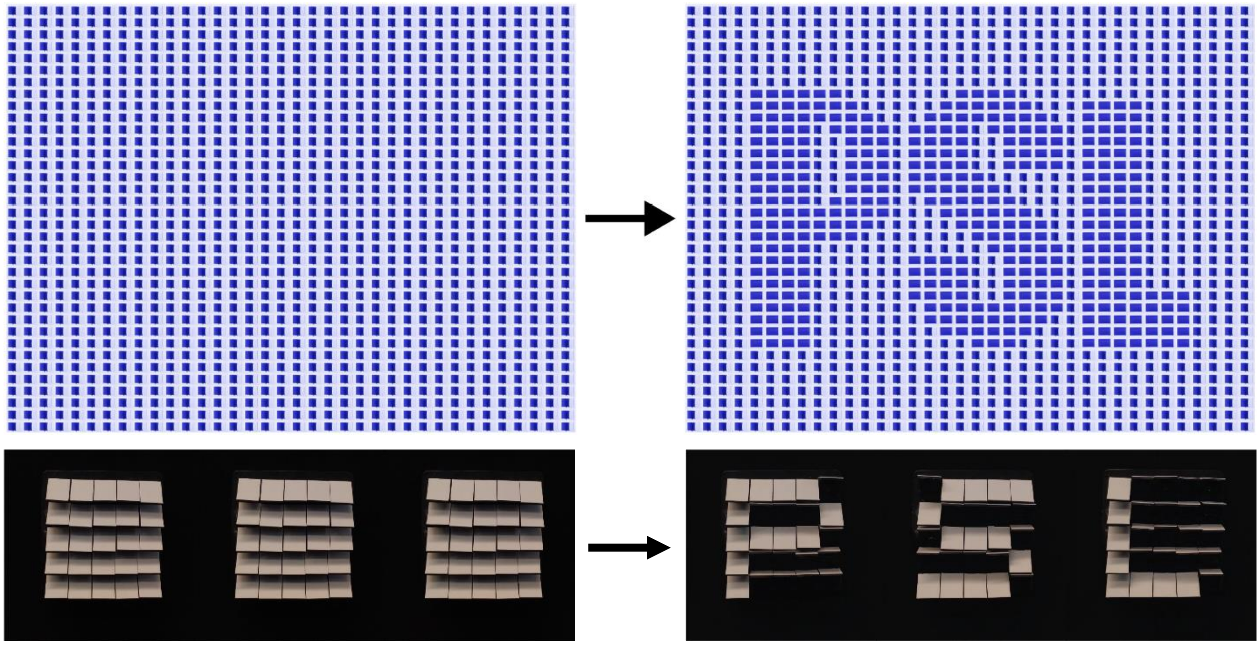

Figure 1.2. a) Tessellation of Programmable Structures Lab (PSL) rendered to elucidate replication of a digital screen using bistable mechanical pixels. More vibrant blue regions are occupied by blue pixels in a pop-down state and less vibrant regions with pixels in a pop-up state. b) Mechxels that leverage bistable switches to create variance in projected area to display characters PSL with a 5 by 5 array per character.

The following papers and conference proceedings have been published as part of this research:

W. K. Chan, K. S. Riley, and A. F. Arrieta, Perceived Value Change via 3D Printed Bistable Structures, in *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2019.

W. K. Chan, K. S. Riley, and A. F. Arrieta, Mechxels: A Preliminary Exploration of Leveraging Bistability for Text and Image Display, in *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2021.

2. MECHXEL DESIGN, FABRICATION AND TESSELLATION PROCESSES

This chapter has been adapted from the conference papers *Perceived Value Change via 3D Printed Bistable Structures* [44], submitted to the proceedings of the ASME 2019 Conference on Smart Materials, Adaptive Structures and Intelligent Systems and *Mechxels: A Preliminary Exploration of Leveraging Bistability for Text and Image Display* [45], submitted to the proceedings of the ASME 2021 Conference on Smart Materials, Adaptive Structures and Intelligent Systems.

2.1 Switchable Multistable (SMS) Mechxel

We create mechanical pixel-based, reversible color change using 3D printed switchable bistability. Switchable multistability arises from the combination of pre-strain and shape memory, enabling us to access multiple elastically programmed shapes at elevated temperatures with fast morphing and low actuation forces, while retaining high stiffness at room temperature. Building on our previous study that achieved multistability through FDM printing with directional pre-stress [1], finite element analysis is conducted to design a pixel-like structure that acts as a unit cell with color change capabilities.

2.1.1 Design and Fabrication

The switchable multistability method leverages the shape memory effect to generate directional pre-strain using FDM 3D printing [1]. During printing, the shape memory polymer (SMP) filament is heated above its glass transition temperature, T_g, becoming rubbery and easily deformable. As the filament is extruded, the polymer chains are stretched in the direction of extrusion. Print settings are adjusted to ensure the polymer quickly cools below its T_g, thereby entering the stiff, glassy state with the chains frozen in this strained configuration, encoding a pre-strain field in the part. The printed part will initially be flat, but when heated above T_g, the polymer chains are free to contract, causing directional shrinkage [1,22]. A bilayer architecture with contrasting pre-strain fields, such as a [90/0] layup, results in a structure that is bistable (Figure 2.1b and c) with fast morphing above the SMP's T_g, but stiff and monostable below T_g [1]. For this research, we use Ultimaker polylactic acid (PLA) filament printed on an Ultimaker 3 Extended.

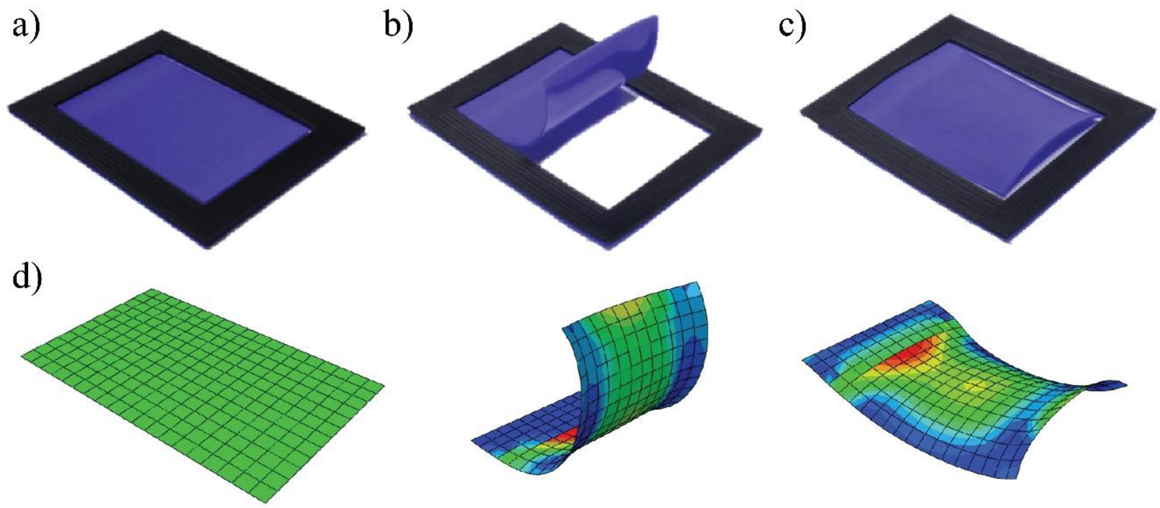

Figure 2.1. a) The Mechxel is printed flat and has two stable states when activated: b) pop-up and c) pop-down. d) Finite element analysis of bistable element of Mechxel showing its pop-up and pop-down states after being heated above its glass transition temperature and swapped between states.

We take a [90/0] bistable rectangular shell as our basic element, with the addition of a narrow [0/0] transition region which connects to a rigid, monostable frame, constraining one short edge [46,47]. The frame controls the shell's orientation when actuated and can also be used to adhere the pixels to surfaces. Finite element analysis using ABAQUS, as described in [48], is used to determine the necessary dimensions to produce bistability with adequate deformation (Figure 2.1d). The pixels tested here have a [90/0] bistable element that is 65 mm x 49.5 mm x 1 mm, a [0/0] transition region that is 10 mm x 49.5 mm x 1 mm and a quasi-isotropic frame that is 2 mm thick and 11.25 mm wide all the way around (Figure 2.1). The printed model consists of four parts: the bottom portion of the frame, top portion of the frame, [0/0] transition region, and central [90/0] element of the pixel. The four parts are modeled in Autodesk Fusion 360 and sliced in Ultimaker Cura. The print directions are defined in Cura. A quasi-isotropic layup is used for the top and bottom frames to minimize deformation. We use a layer height of 0.1 mm and print the pixels using dual extrusion of PLA. The choice of filament color is based on light primaries (i.e. blue, red and green) [49]. The frame is split into top and bottom sections in order to print the bottom portion with the same filament as the bistable element for print continuity, while the top portion is printed in a neutral color (i.e. black or white) to match the background color used for documentation.

Although this proved the concept of changing perceived value through material deformation, the original Mechxel's size was not practical for manufacturing the large quantities needed for tessellation purposes because of the amount of material and print time (74 minutes) required per pixel. The size also limited the image resolution in terms of the physical space for tessellation. However, by decreasing the print's layer height, pre-strain has been observed to increase [1,22]. This allows for reduced dimensions while still achieving similar deflections, thus reducing overall Mechxel size. Through conducting numerous finite element simulations with the commercial software ABAQUS, using a similar process as for the initial size, we successfully reduced the length and width of a pixel to a quarter of the original dimensions while retaining bistability and enough deflection for a sufficient visual difference between the two states. Although a smaller Mechxel geometry would maintain its bistable properties, simulations showed that the difference in deflection between its two states would be less pronounced due to the linear reduction of pre-strain with the side length [50]. The final size we used consisted of a bistable element measuring 14.63mm x 12.38mm x 0.8mm with a transition region of 4mm x 12.38mm x 0.8mm and a 1.8mm thick and 3mm wide quasi-isotropic frame. This Mechxel geometry is 1/16th of the area of the original mechanical pixel (Figure 2.2), which results in a significantly reduced print time of 11 minutes, 85% faster than the initial size. This model was then sliced using Cura and printed on an Ultimaker 3 Extended with a layer height of 0.05mm.

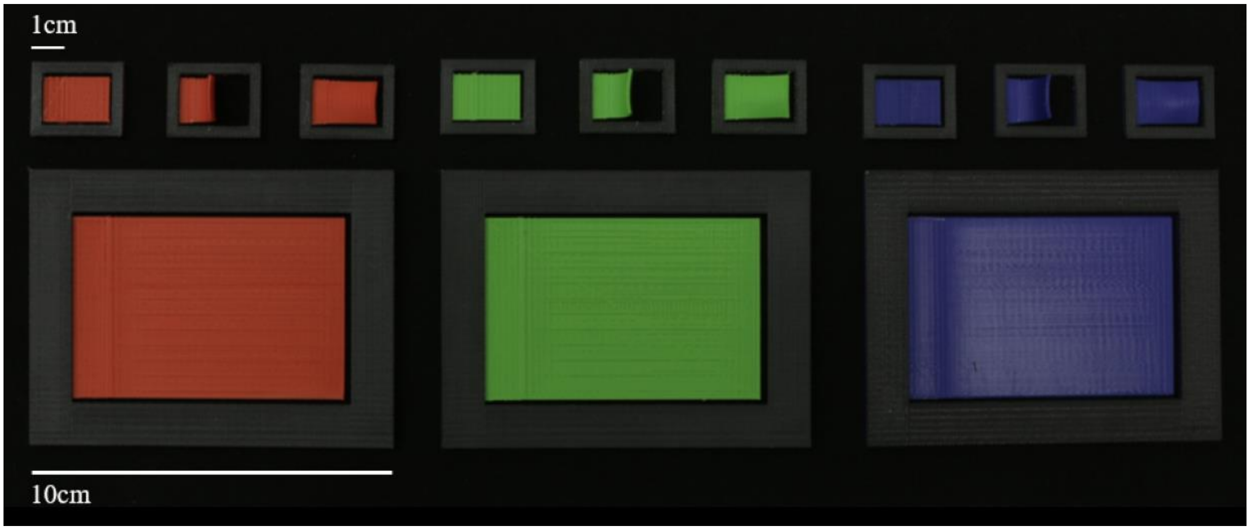

Figure 2.2. Miniaturized Mechxel (top) in comparison to original mechanical pixel design (bottom). The new Mechxels are each shown in the printed, pop-up, and pop-down states from left to right for each color.

2.1.2 Mechxel Activation into Stable State

With a reduction in print layer height from the original 0.1mm to 0.05mm we observe a directional shrinkage of 11.1% compared to 5.5% at 0.1mm layer height when activated at 65°C for 2 minutes [1]. The pre-strain is released by heating PLA above its glass transition temperature, T_g, causing it to become compliant and shrink in the direction of print extrusion to release the pre-strain from FDM. To keep the frame rigid during the activation process, the top layers of the frame were printed with acrylonitrile butadiene styrene (ABS) due to its higher T_g, meaning it will remain stiff with minimal thermal deflection, while the PLA layers of the frame ensure print continuity with the pixel transition region. We activated the Mechxels through immersion in water at $T_{activation} = 65°C > T_g = 60°C$ [1,22] and manually actuate them to their different stable states. This process was repeated until the number of desired pixels was obtained for the tessellation, study and evaluation.

2.1.3 Tessellation Rendering

To resolve images and characters with Mechxels without unnecessarily expending material through trial and error, digital tessellations can be created of text and images. Initially, we manually tessellated the Mechxels by arranging Mechxels in their various states by tracing and filling the outline of an image in Adobe Illustrator. This process requires establishing a user defined swatch of a single Mechxel and manual scaling of the swatch derived pattern, resulting in inaccurate alignment and inconsistency of resizing between the various pixel images. In order to systematically and consistently render a simulated tessellation of an image using Mechxels, we developed a program to accurately render the tessellation using images of the Mechxel's two states (Figure 2.3a).

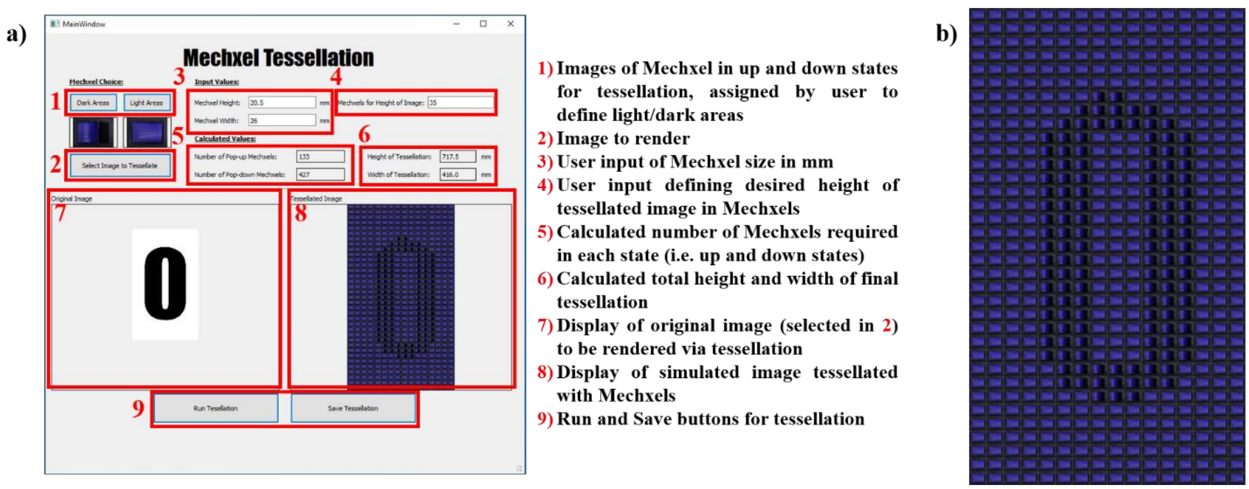

Figure 2.3. a) Mechxel tessellation program displaying original image to be rendered with Mechxel and the resulting tessellation b) Sample output image from image tessellation program with a specified height of 35 Mechxel.

This algorithm utilized the OpenCV image processing library [51] to tessellate the image and PyQt5 [52] to establish the interface, requesting user input for the image that will be tessellated and images of Mechxels for tessellation (i.e., images of the Mechxels in their up and down states). We can then specify the number of pixels that would be used to tessellate the height of the image and size of the actual Mechxel. Subsequently, the algorithm scales the images of the Mechxels to fit the user specified number for the height of the image, while also calculating the number of Mechxels for the width of the image. Since the Mechxels used for tessellation only have two states, for this proof-of-concept exploration, the image to be tessellated is first converted into a binary image (i.e., a monochromatic image defined by 0s and 1s, where 0 corresponds to an off state and 1 corresponds to an on state, which are perceived as black and white respectively [53]) to both reduce the noise and simplify the tessellation process. These binary states correspond to the state of each tile - with the pop-up state being a 0 and the pop-down state being a 1 (i.e. darker and lighter values respectively).

Blocks of pixels from the image are then isolated and the average intensity calculated to determine which Mechxel image will be used for that area of the image. Within a code execution time of 0.5 seconds, this process is repeated until the entire image has been processed and tessellated, as shown in Figure 2.3b. Thereafter, the tessellated image is displayed alongside the original image for comparison. The program will also calculate the number of Mechxels in each state required to recreate the image as well as the real scale of the physical tessellation, thus easing the arrangement process with the printed pixels. The program further allows us to iterate this process by varying the number of Mechxels used to tessellate the image to obtain the number of pixels that we determine will best resolve the target image. We can then save the tessellation with the "Save Tessellation" button at the bottom of interface. Using this process, we can view the tessellation prior to manufacturing and predict the necessary scale and amount of print material.

2.2 Bistable Switch Mechxel

2.2.1 Inspiration, Design, and Fabrication

The second Mechxel design takes inspiration from the open-source bistable switch project by Brigham Young University's (BYU) Compliant Mechanisms Research Group (CMR) [54]. The design of the switch is based on a four-bar linkage and was made available on Thingiverse for educational purposes as an introduction to the concept of bistable and compliant mechanisms. The available files include both the part drawing file and the stereolithographic (STL) file [18] that can either be FDM 3D printed or modified to user specifications from the drawing. As printed, the switch measures 109mm x 50.0mm x 8.9mm and suggested manufacturing methods apart from FDM 3D printed including CNC milling which claims to have a longer life cycle than the former.

As the switch is manipulated from one equilibrium state to another, an angle change in the top area of the switch can be observed. If the switch is viewed normal to the top faces, the angle change results in a difference in perceived area of the top surfaces and thus can be used to for display due to visual difference between each state. Because the design was not made for any specific application beside an educational demonstrator targeted at curious makers and students, modifications had to be made to the geometry so that it would be useful for this application for a bistable display.

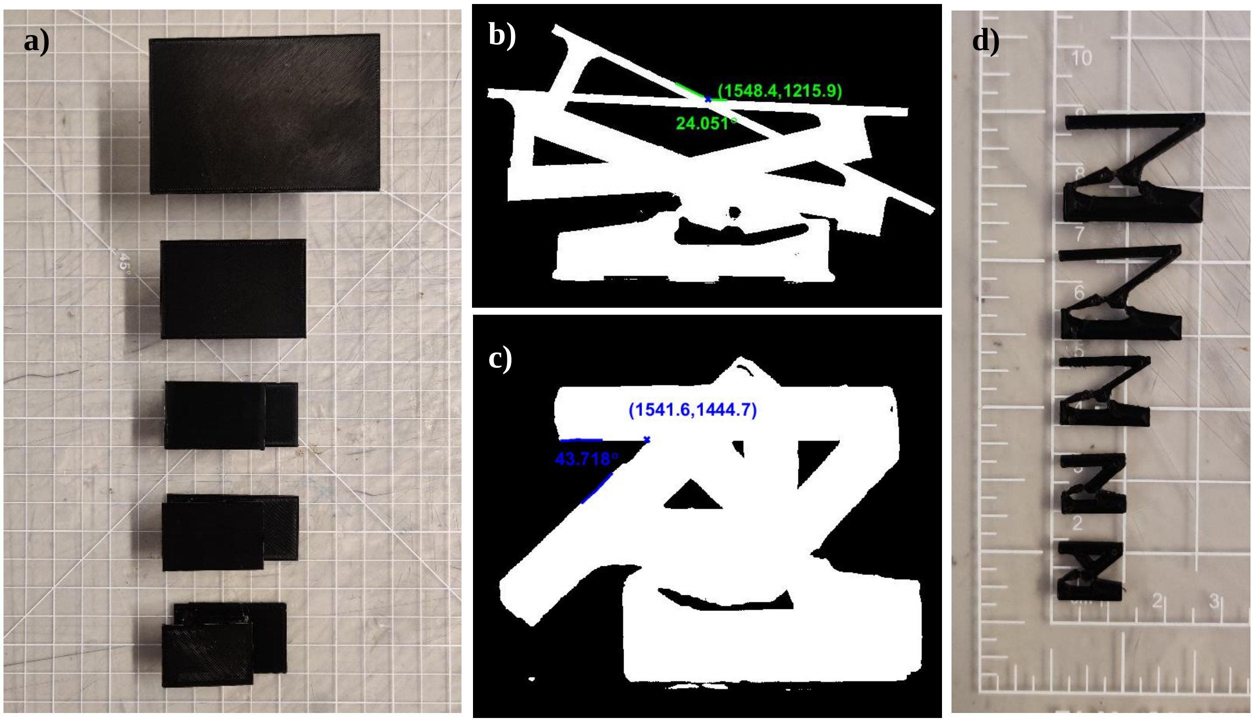

Figure 2.4. a) Initial angle measurement of BYU switch with a horizontal plate surface with a measured angle of 24.051°. b) Iteration of Mechxel switch with an angle measurement of 43.718°. c) Documentation of switch iterations during miniaturization process.

Using the STL and drawing file provided, the switch was first imported, recreated and dimensioned in SolidWorks to create a fully constrained part. Additions were then made to understand the range of the motion of the switch by printing the switch which included an additional flat surface that was parallel to the switch's horizontal base. This modification can be seen in Figure 2.4a as the black rectangular tile mounted on top of the switches. An estimate of the change in angle was then conducted using image processing in MATLAB [55] using the horizontal surface as a reference point. This was achieved by taking images the switch in each of the two stable states then superimposing binary images of them onto each other to create an intersecting region to obtain the difference in angle between their stable states. The resultant change in angle was determined to be 24.051° (Figure 2.4b) which, although sufficient displacement to perceive a visual change in the switch. This design could still be further optimized by increasing the change in angle to achieve greater visual difference between each stable state. In addition, comparing the size of the switch to the SMS Mechxel, the switch was designed significantly larger in size. Assuming that the area of a display remains constant, a smaller Mechxel size, would increase the resolution of the display, thus the capability to reduce the switch size was also investigated.

Through an iterative process of downsizing the two main components of the bistable Mechxel and the increasing the angle of deflection by manipulating the geometry of the switch and the switch and colored tile is designed with dimensions fitting in an area of 10mm x 10mm with a thickness of 1mm (Figure 2.4d). This new design was then sliced in Cura and manufactured using both the Ultimaker 3 Extended and the Ulitmaker 5S. As the features of this new design are significantly smaller than the initial STL file, the printer nozzle had to be changed to a 0.25mm diameter nozzle from the standard 0.4mm and printing parameters had to be adjusted to account for thin features in the model, particularly the living hinges which were printed with 2 print lines to ensure that linkages of the mechanism were attached together (Table 2.1). The prints were made in ABS due to the material's higher stiffness and durability. Manually testing the cycle limit of an arbitrary sample, over 800 cycles could be achieved before the switches were damaged and bistability lost.

Table 2.1. Printing parameters in Ultimaker Cura for minaturized bistable switch fabrication.

Nozzle Diameter	0.25mm
Layer Height	0.1mm
Line Width	0.14mm
Print Speed	20mm/s
Infill Density	30%

Using the same image analysis technique in MATLAB the angle of deflection increased to 43.718° as shown in Figure 2.4c. However, this was still insufficient to provide a complete value change from black to white or vice versa. Leveraging changes in observer angle and the new deflection capabilities of the switch, the angle that the tile makes with the horizontal could now be changed to appear as a uniform square from a 2° observer angle from the top view. Assuming the tiles are homogenously lightened, a surface incline of 45° would allow the projected area normal to the Mechxel grid to be viewed as a colored square. When snapped, the colored surface of the tile is perpendicular to the viewer, obstructing the view of the tile's colored surface entirely. This shape morphing results in a change of the viewer's perception as now only the background of the tile is visible.

Taking these design factors into consideration, the exploded view of an individual bistable Mechxel can be seen in Figure 2.5. To enhance the assembly, replacement, and manipulation of the Mechxel, additional design considerations were considered. The first modification was a lever system that extended below the base of the Mechxel, allowing the state of the Mechxel to either be changed from the front, by flipping the Mechxel itself, or from the back, by manipulating the switch. During design iterations, to assist with the rapid prototyping, reusability, replacement and durability of parts, modifications such as snap-fits between the switches and the base, geometric limit stops and slide-fits between the colored tile the switches were also introduced (Figure 2.5b). This allowed the quick and easy replacement of damaged Mechxels.

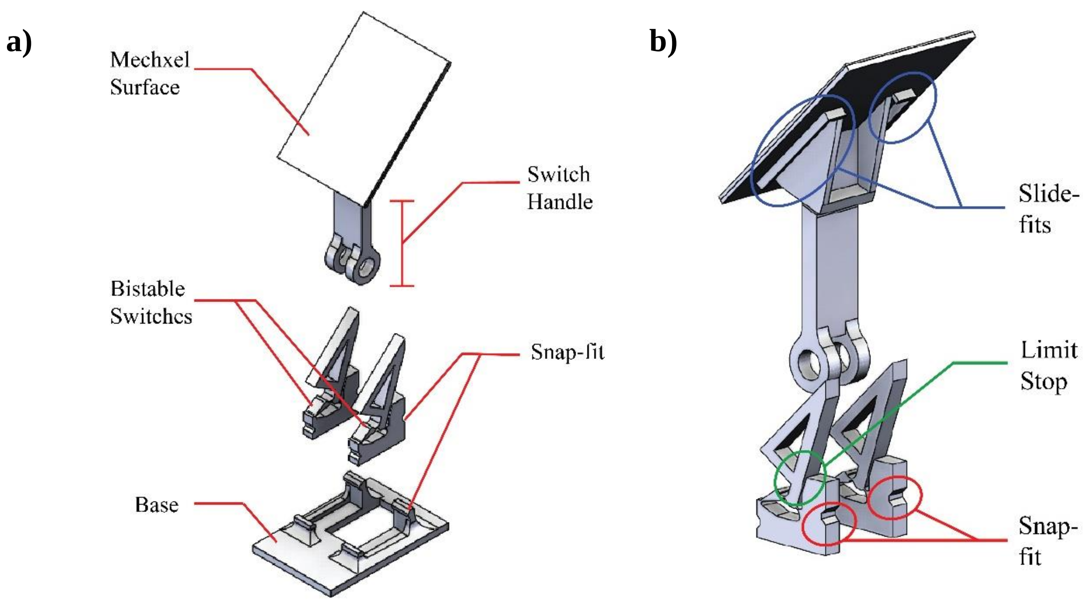

Figure 2.5. a) Components of the assembly, including the final switch design, Mechxel and base. b) Design of snap-fits (circled in red), limit stops (circled in green) and slide-fits (circled in blue).

This new design was then sliced in Cura printed as three separate components – the base and switch with ABS, and PLA for the colored tile. The colored tile comprised of two thin layers of white PLA for the viewer facing panel and black for the body of the rest of the component. Prior to assembly, the white faces were then coated with a flat white layer of spray paint to ensure that the color of the tiles were homogenous across their surface. 25 Mechxels were then manufactured in for the assembly of a 5-by-5 Mechxel grid. Previous iterations can be seen in Figure 2.6.

Establishing two different designs to achieve color change from mechanical multistability allows for the generation of contrast changes and the ability for the display of characters through deflection. This constitutes the core of the Mechxels color change method. In the following chapters, we develop this method into the implementation of a tessellated display as well as verification of this method through preliminary image processing.

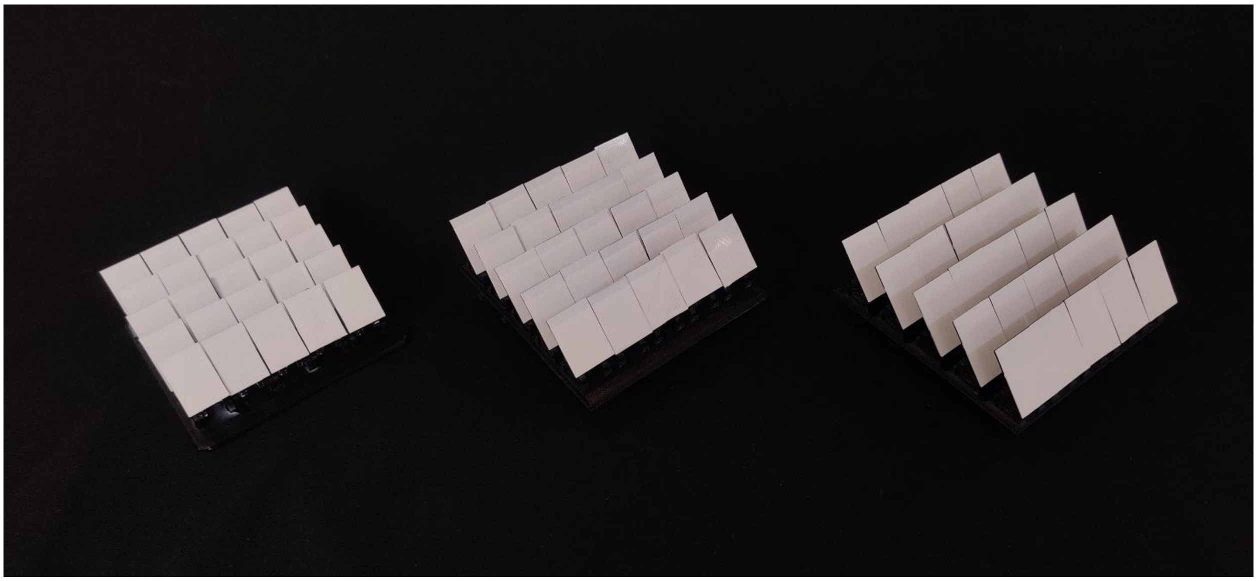

Figure 2.6. Iterations of designs from earliest Mechxel panel (left) to latest panel (right) with modifications accounting for using a “handle” that would allow manipulation from the back. Tolerance considerations were also accounted for ensure that the tiles were freely moving and did not collide with adjacent tiles during manipulation between states.

3. ANALYSIS AND RESULTS

This chapter has been adapted from the conference papers *Perceived Value Change via 3D Printed Bistable Structures* [39], submitted to the proceedings of the ASME 2019 Conference on Smart Materials, Adaptive Structures and Intelligent Systems and *Mechxels: A Preliminary Exploration of Leveraging Bistability for Text and Image Display* [40], submitted to the proceedings of the ASME 2021 Conference on Smart Materials, Adaptive Structures and Intelligent Systems.

3.1 Switchable Multistable Mechxels

Quantitative and qualitative analysis is conducted through image processing techniques to proves the viability of this approach to creating value change through geometric deformation of bistable structures. The Python program developed assists with the tessellation by using image processing to tessellate the image and providing an interface in which images are mapped to their tessellated equivalent in Mechxels. This minimizes trial and error and determines the physical size of the tessellation and number of Mechxels required.

3.1.1 Color Analysis

Photographic documentation was captured in 8-bit 256 units of color on a Canon 70D Digital Single-Lens Reflex (DSLR) with a 40mm f/2.8 lens using the settings specified in Table 3.1 with a custom white balance adjusted for the setup environment (Figure 3.1).

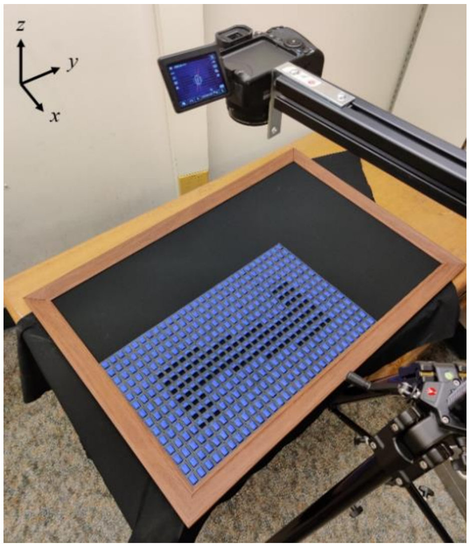

Figure 3.1. Setup for photographic documentation in a homogenously lit room.

Table 3.1. Camera settings for photographic documentation

Camera	Canon EOS 70D
Lens	40mm f/2.8
Shutter Speed	1/2s
Aperture	F14
ISO	100
White Balance	Custom

The MATLAB script we used was adapted from a code for the analysis of color intensity and luminosity [56] using simple color segmentation into an image's RGB components and displaying each component individually in a histogram. In doing so, we can observe the intensity differences of the color of interest of each Mechxel. The value change exhibited by the Mechxels is apparent in the RGB histograms of each color of the light primaries (Figure 3.2). These histograms show the number of pixels (y-axis) at each color intensity in 256 color (x-axis). Because extreme intensity values are indicative of under or overexposure [57], for the purposes of this analysis, we ignored the leftmost peaks of the histograms. These low intensity values capture the black frame and background, while the central peaks indicate the intensity of the color of interest. The changes in these central peaks illustrate the shift in value between stable states. This change in color intensity from lower to higher bit values quantifies our visual perception, indicating that there is an overall change in the saturation of the image. This implies that we are seeing either more or less color as the peaks shift along the x-axis of the graph. For instance, the peak of the blue mechanical pixel (Figure 3.2a) between the bit values of 100–200 is seen to increase when the pixel changes from the pop-up state to the pop-down state. This indicates a quantifiable change in color intensity between states which manifests itself to human eyes as a change from a more intense blue (pop-down state) to a less intense blue (pop-up state). Similar shifts are observed for the peaks between bit values of 100–200 for the red (Figure 3.2b) and green (Figure 3.2c) pixels. This indicates the same change in perceived value from a brighter shade of red or green (pop-down state) to a less intense one (pop-up state). We also ran the same MATLAB analysis to examine the value change between their respective states of the smaller Mechxels and observed similar results as the bigger Mechxels (Figure 3.3).

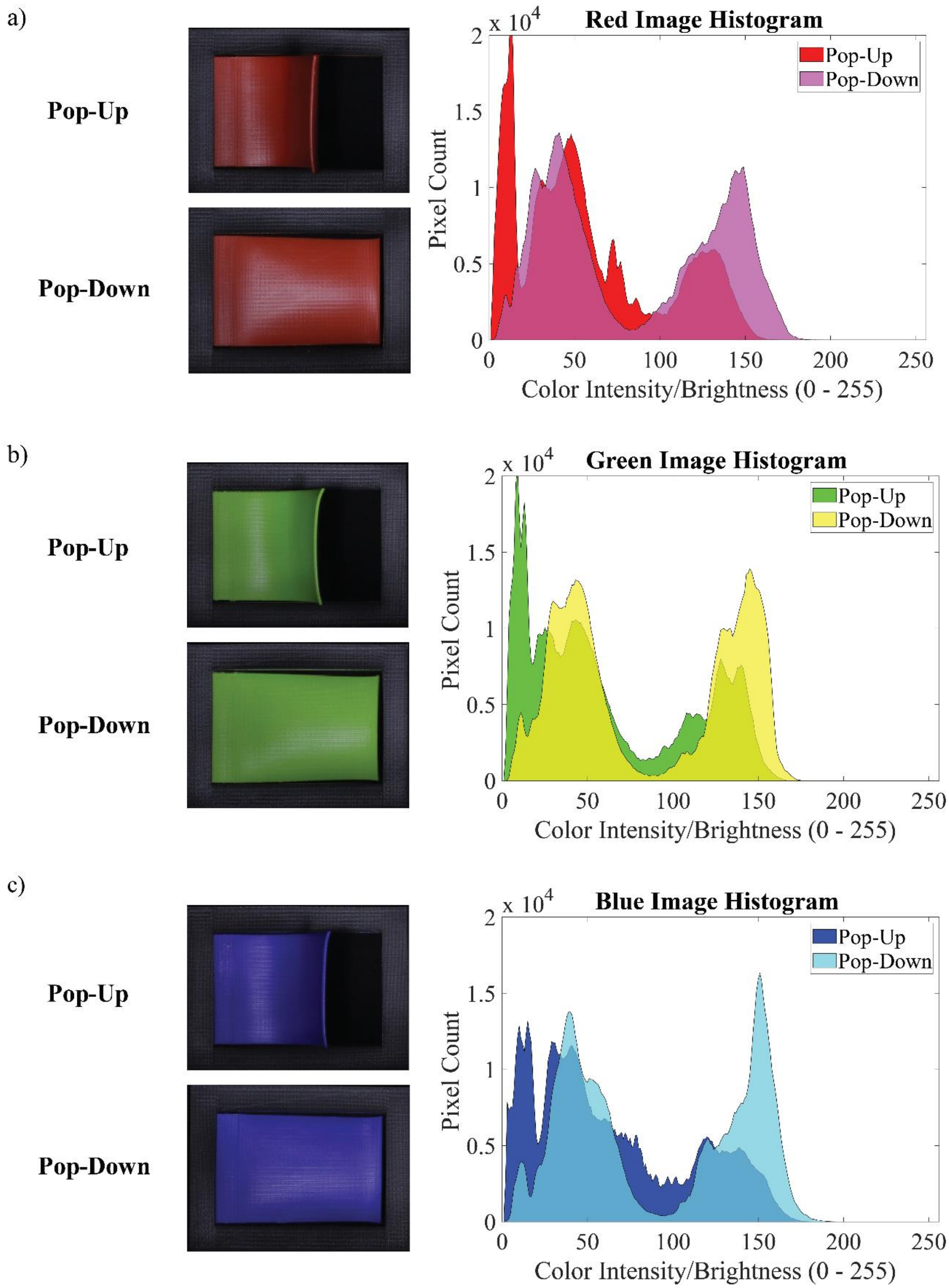

Figure 3.2. Documented images and isolated intensity histograms of a) blue, b) red, and c) green original size Mechxels in their pop-up and pop-down states, displaying differences in observed color Intensity between each state.

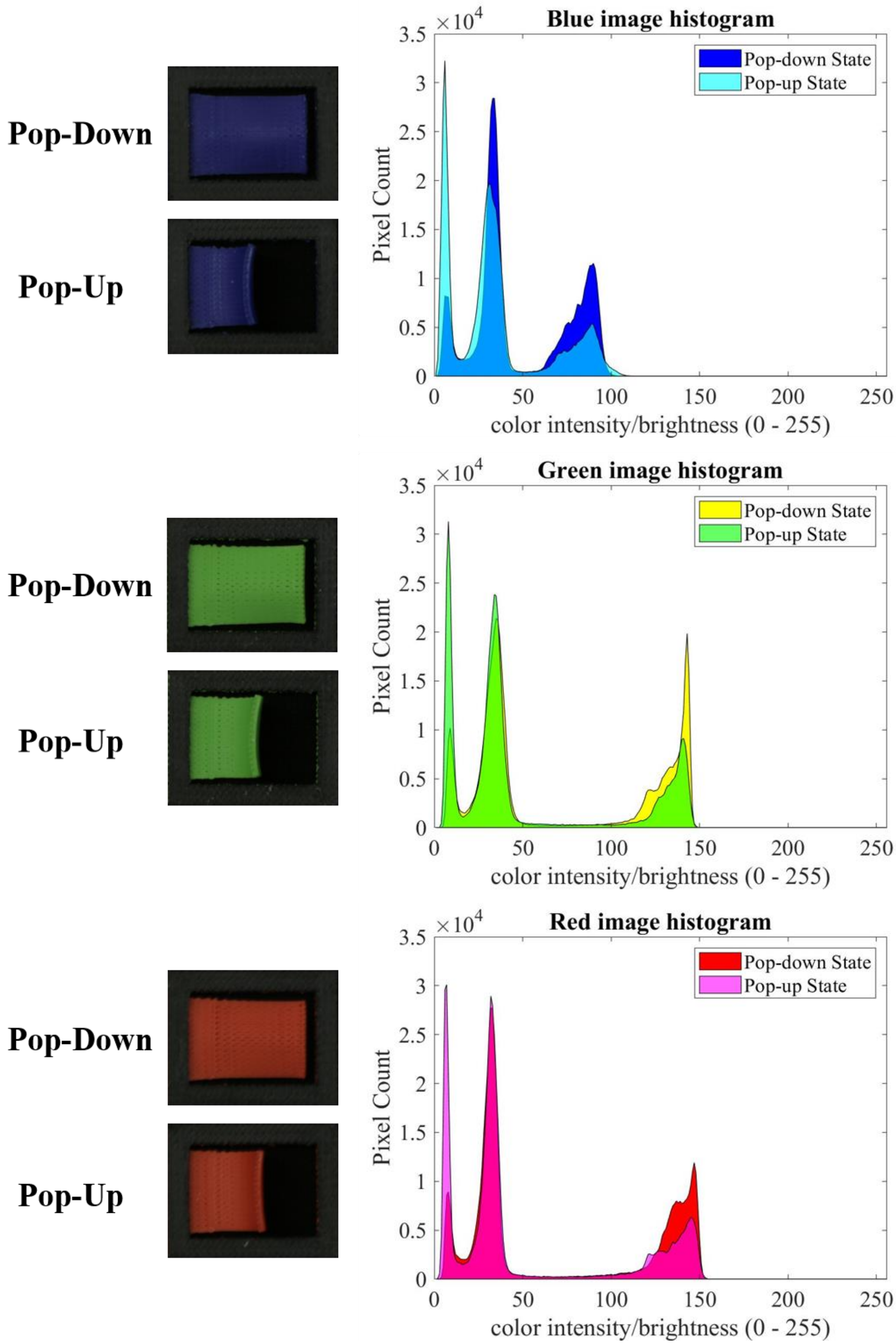

Figure 3.3. Isolated intensity histograms of blue, green and red miniaturize Mechxel in their respective up and down states, exhibiting similar changes in observed color intensity between states as their original size counterparts.

3.1.2 Tessellation Processes for Switchable Multistable Mechxel

To examine the effectiveness of replicating characters and images, the height of the image was tessellated in increments of 5, from 5 to 50 Mechxels using photographs of the Mechxel geometry for the character “0” (Figure 3.4a). We generated digital tessellations of the images using the developed tessellation program to calculate the number of pixels required for a variety of alphanumeric characters. The Impact typeface with a 100-point size was used due to the large surface area of each character. The character set included numbers from 0 to 9 and capitalized A to Z. Figure 3.4a show the results of the digital tessellation of the character “0” with a varying number of Mechxels defining the height of the image to examine the change in resolution of the image with an increasing number of Mechxels used for the tessellation. A height of 35 Mechxels was used to tessellate the remaining characters with the width varying based on the width of each character as displayed in Figure 3.4b and Figure 3.4c. These digital tessellations were then used as reference images to create the physical tessellation in a 24in x 36in frame with a black background and photographically documented (Figure 3.1). We adjusted the height and width of the physical tessellations slightly during the tessellation process to reduce any unused space around the edges of the background that were not critical to resolving the subject matter. For exploration purposes, tessellations of the various characters were also done digitally in the other two light primaries – red and green, but they were not implemented physically (Figure 3.5).

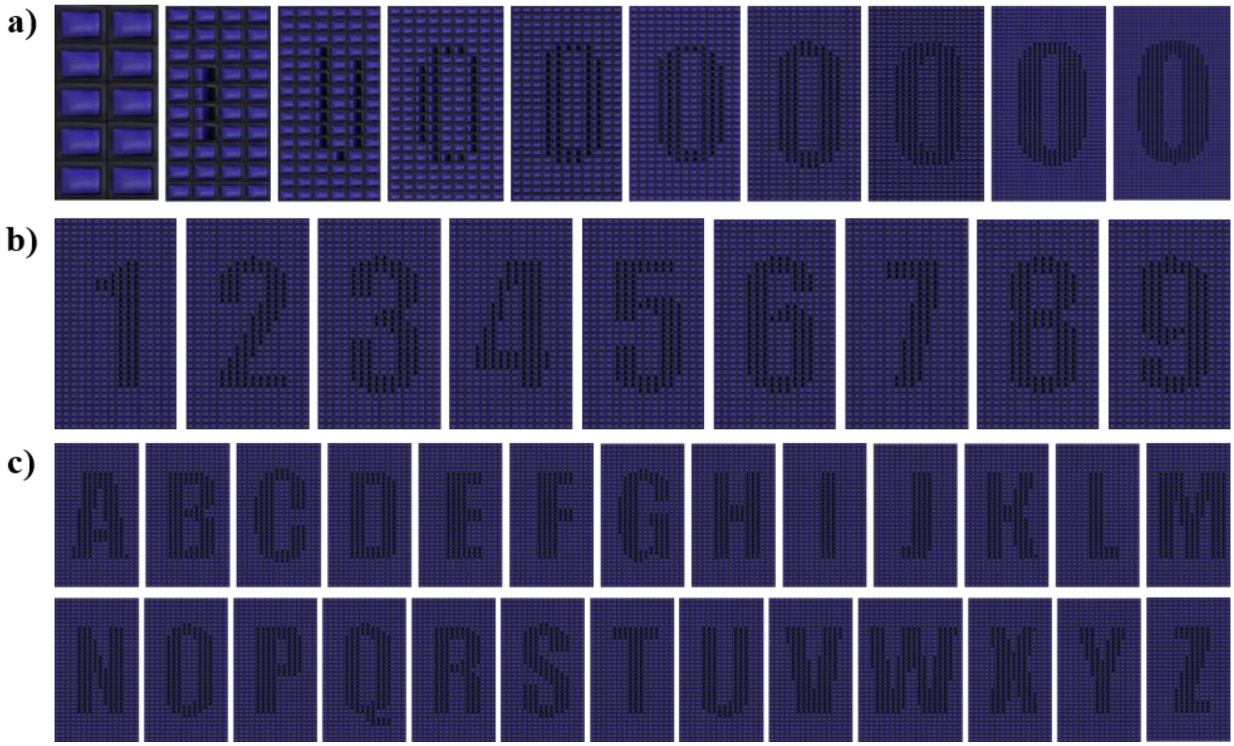

Figure 3.4. a) Digital tessellation of the numerical character “0” with height of 5 to 50 Mechxel in 5-mechxel increments. Horizontal pixel density is increased proportionally. b) digital tessellation of numerical characters “1” to “9” with a height of 35 Mechxel with varying widths determined by each character. c) Digitally tessellated characters (a-z) with a height of 35 Mechxel. All characters are in Impact font.

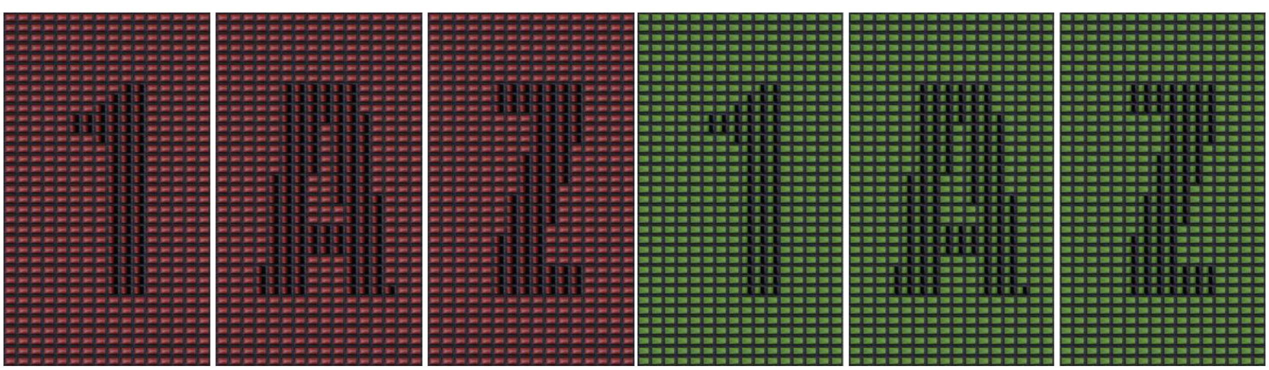

Figure 3.5. Sample digital tessellations of characters 1, A and Z in red and green color primaries.

Using the tessellation program, tessellations were first rendered digitally to determine the required number of Mechxels, and thus an estimate of manufacturing material volume, time and the tessellation's overall physical size. We then printed the required number of Mechxels, activating and snapping them to the required up and down states. The renders are used as a reference to construct the physical tessellation out of the 3D printed Mechxels. As the digitally tessellated characters shown in Figure 3.4 were distinguishable to the eye, sample characters of 1, A and Z were chosen to be evaluated for accuracy through digital overlay and an OCR software [58]. Prior to conducting OCR, the documented images are first converted to grayscale without changing the contrast and brightness, and a gaussian filter is applied to reduce the gaps created by the frame of the Mechxels before processing through the OCR program. This allows us to have a basic evaluation of whether the characters are recognizable by a computer.

3.1.3 Results

As shown in Figure 3.6a, we can observe that the tessellation sufficiently captures the original characters, measuring 594.5mm by 364mm, fitting comfortably within the frame. However, due to the size of the Mechxels relative to the overall area, curved and angled edges are not as resolved, appearing like a low-resolution bitmap image. In comparison to the digital tessellations, the physical tessellations of Mechxels have minute imperfections, such as the inconsistency of deflection due to varying pre-strain from printing irregularities. This resulted in the deflection of some Mechxels to be less pronounced compared to others, resulting in slight variance in perceived coloration due to lighting. Even so, the tessellated characters are easily distinguishable and are even sufficiently resolved to be viewed from different angles (Figure 3.6b).

As shown in Figure 3.6c, the OCR algorithm successfully recognizes the individual characters rendered by the physical tessellations. This suggests the capability of Mechxels to render alphanumeric characters recognizable to the computer.

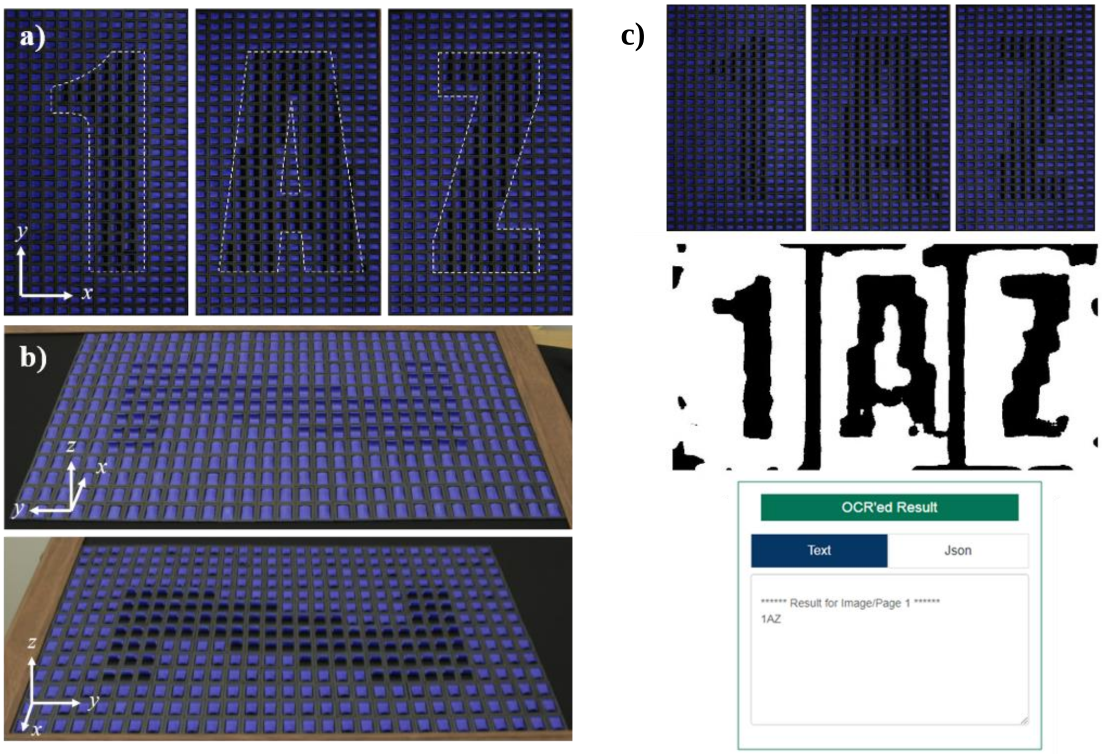

Figure 3.6. a) image of physical tessellation overlaid with binary character image reference for characters 1, A and Z. b) documentation of physical tessellation from two arbitrary viewing angles. c) OCR results of physical tessellation of Mechxels for sample characters 1, A and Z. Conversion from digital image to binary before OCR is performed.

3.2 Bistable Switch Mechxel

To study the bistable switch Mechxels, emphasis was placed on the character production and a comparative analysis of the physical grid display and their corresponding reference images. Although the contrast of the SMS Mechxels was sufficient to resolve the tessellated characters in the typeface Impact, further investigation into the appropriateness of the typeface and method of display had to be conducted. Using the bistable switch Mechxels, which resulted in a clear contrast between states (i.e. white and black) and minimized gaps between tiling, we were better able to study the ability of this deformation-based display method to replicated a specific but easily accessible typeface through simple comparative image analysis methods.

3.2.1 Font Choice for Text Display

The font choice, though successfully in replicating the characters using the SMS Mechxels, was not the optimum choice to demonstrate character displays due to the curves in the Sans Serif typeface Impact. In typography, a typeface refers to a particular set of glyphs that share a common design, the font on the other hand is a subset of a particular typeface [59]. For instance, within the typeface Impact, a 12-point character is not the same as a 10-point character, they are different fonts from the same typeface. Sans Serif typefaces are identified by their even stroke thicknesses, and lack of flourishes such as a foot on characters such as “i”. On the other hand, Serif typefaces have small decorative flourishes at the ends of the strokes and often vary in terms of stroke thicknesses within each character. These variations in stroke thickness in Serif typefaces and smooth curves in Sans Serif typefaces make it difficult to replicate text using such low-resolution methods such as the Mechxels with their straight edges and relatively large physical size compared to digital pixels. As such, a more apt typeface needed to be used to create a reasonable direct comparison Mechxel text replication and their reference images. These typefaces would have to have similar characteristics to the low resolution 8-bit displays that were initially used in gaming consoles and LCD screens.

To achieve this comparison, the font Silkscreen is determined to be highly suitable for the implemented text display. This typeface, created Jason Aleksandr Kottke, can be easily accessed, downloaded, and installed from open source, custom font websites such as Font Squirrel [60] and DaFont [61]. This typeface represents most of their alphanumeric characters and symbols within a 5-by-5 grid and is one of the few typefaces that use a minimum number of pixels to represent each character. Furthermore, this typeface has no lowercase instances of each character, reducing the number of positions and orientations each character can appear within the grid. By constructing a 5-by-5 grid of Mechxels as show in Figure 2.6, the characters of this typeface can easily be physically reproduced, and a comparison of its accuracy can be performed using basic image processing.

For this comparative analysis, some of the characters are left out due to the dimensions of the grid manufactured. This is due to the size of the characters which would require a 6-by-6 grid instead of the already manufactured 5-by-5 grid of Mechxels. These characters included the regular character “Q”, and bolded characters from “A” through “Z”. Even though these characters were omitted from testing, characters such as “Q” and other characters that requires 6 units in length and breadth can easily be factored in by increasing the Mechxel tile grid size to a 6-by-6 to include these characters.

3.2.2 Text Display Using Mechxel Paneling and Analysis

For the purposes of this analysis, a number of orientations are used to compare the digital analysis with the manufacture grid of Mechxel tiles. Using Adobe Illustrator, the reference images were created using the typeface Silkscreen. This was done by first defining a square canvas in Illustrator. The character of the typeface was then typed out, converted to an outline, scaled, and aligned to fit the entire canvas in a fix orientation and position. This processed was then repeated for each character except for “Q” as mentioned above. In cases where the character did not fill up the canvas, the other positions and orientations were also defined. An example of all the possible positions for the character “A” can be seen in Figure 3.7a in both regular and bold. These included orientations in 0°, 90°, 180° and 270° rotations. Out of all these possible orientations, the one of each orientation was taken to be replicated in using the 5-by-5 Mechxel grid (Figure 3.7b).

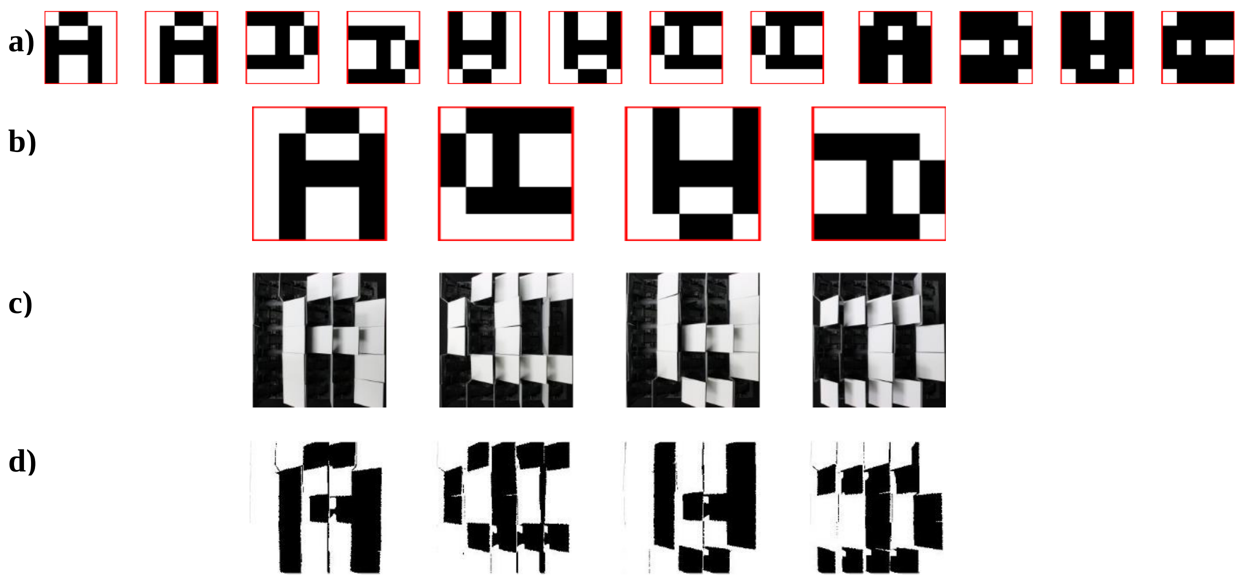

Figure 3.7. a) All possible orientations and positions of sample character “A” in Silkscreen typeface with the character’s bounding box outlined in red. Other characters, like “A”, use significantly less space, allowing more than one position of the character within the bounding box. b) The four orientations and positions of the character “A” used for the analysis. c) The documented tiled images of “A” in their corresponding orientations and positions as the reference images. d) Preprocessing results of documented images to binary equivalent.

This was done for all included characters. Thereafter, the matching positions were documented using the Mechxel grid as shown in Figure 3.7c with all the tiles angled towards the left. Documentation was conducted using the Canon 70D Digital Single-Lens Reflex (DSLR) with a 40mm f/2.8 lens using the settings specified in Table 3.2 with a custom white balance adjusted for the setup environment. The documentation also assumes a top-down view of the Mechxel grid, taking up the entire field of view to avoid cropping during image preprocessing.

Table 3.2. Camera settings for photographic documentation of 5-by-5 bistable switch Mechxel grid.

Camera	Canon EOS 70D
Lens	40mm f/2.8
Shutter Speed	1.6
Aperture	F14
ISO	100
White Balance	Custom

As observed, although the tiles are designed to consider a binary display of black and white, the colors used are a complement of the reference images. Therefore, preprocessing was conducted prior to analysis. The documented and references images were first all batch imported into MATLAB, the reference images were then resized to match the size of the documented images, thereafter, the images were converted into grayscale before converting them into binary complements of their grayscale images.

To analyze the similarity of the images between the reference and documented images of characters, each documented image is matched up against its corresponding reference image in orientation and position. The Sorensen-Dice coefficient is then used as the means to correlate the precision of the documented characters to their reference images [62]. This coefficient is a statistical tool to measure the similarity between two sets of data and has been commonly used in the validation of image segmentation as well as a variety of other applications pertaining to natural language processing [62]. Using MATLAB’s Image Processing Toolbox, this coefficient is computed for each of the image pairs, using the reference image as the ground truth image and the documented Mechxel grid as the test totaling 100 comparisons for 25 characters in 4 positions and orientations. In cases where characters are symmetric about their diagonal, vertical and horizontal axis, such as “X”, four samples were still used for the analysis in order to consider possible impact due to manufacturing defects that would cause the tiles to not consistently realign to the same position each time the character was tessellated. Additionally, a pixel-by-pixel comparison between the reference images and documented images is also conducted in this analysis. This entails taking the sum of all the pixels that differed between images divided by the total resolution of the image, resulting in the error between the reference image and the Mechxel grid.

3.2.3 Results

The values of the calculated Dice-Sorensen coefficients for the characters “A” to “Z” (without “Q”) were obtained as shown in Table 3.3 at the various positions and orientations. With most of the values obtained having an average of 90.0% similarity between the documented and reference characters. The lowest values can be observed to occur for characters “N” at 0° and 90° orientations, “H” at 180° orientation and “B” at a 270° orientation with respective precisions of 83.1%, 84.1%, 84.8% and 84.5% respectively. The character with the lowest average precision is determined to be “N” with an average of 85.2%. On the other hand, the character with the highest precision is “I” with an average value of 95.7% across all orientations. Overall, there is a high correlation between the documented image to the digitally constructed references character images.

Table 3.3. Sorensen-Dice coefficients calculated between documented and reference character images for the “A” to “Z” (except for “Q”). Values with the highest precision have been highlighted in green and lowest in red.

	0	**90**	**180**	**270**
A	0.893	0.898	0.871	0.872
B	0.878	0.912	0.849	0.845
C	0.917	0.930	0.911	0.902
D	0.887	0.911	0.863	0.863
E	0.909	0.924	0.880	0.877
F	0.929	0.932	0.888	0.919
G	0.907	0.908	0.856	0.885
H	0.886	0.899	0.847	0.865
I	0.977	0.979	0.939	0.934
J	0.938	0.920	0.937	0.906
K	0.909	0.929	0.882	0.893
L	0.938	0.964	0.930	0.910
M	0.849	0.846	0.853	0.885
N	0.831	0.841	0.868	0.867
O	0.911	0.902	0.901	0.891
P	0.902	0.927	0.875	0.908
R	0.897	0.892	0.860	0.881
S	0.921	0.882	0.910	0.908
T	0.969	0.965	0.912	0.911
U	0.912	0.923	0.900	0.888
V	0.917	0.922	0.902	0.912
W	0.842	0.871	0.856	0.866
X	0.881	0.904	0.897	0.911
Y	0.935	0.933	0.910	0.939
Z	0.935	0.876	0.908	0.892

As for the computation of the observed error between documented and reference images, the highest and lowest values can be found in Table 3.4 below. In each orientation, the highest precision to the reference was identified in characters “I” at 0° and 90°, “J” at 180° and “Y” at 270° orientations with percentage differences between documentation and reference character of 3.7%, 3.3%, 9.1% and 8.8% respectively. On the other hand, the lowest precision was observed for characters “N” at 0° and 90°, “H” at 180° and “B” at 270° orientations with percentage differences between documentation and reference character of 17.4 %, 16.5%, 16.6% and 15.8% respectively. Overall, the character with the highest average error from all four orientations, was the character "N" at 15.3% and the lowest being "I" at 6.7% which correlates to the precision calculated using the Sorensen-Dice method above.

Table 3.4. Calculated difference between binary reference and documented images of characters "A" to "Z" (with the exception of "Q") during pixel-by-pixel comparison.

	0	90	180	270
A	0.116	0.111	0.140	0.140
B	0.126	0.088	0.155	0.158
C	0.107	0.090	0.116	0.127
D	0.122	0.095	0.150	0.150
E	0.107	0.088	0.139	0.143
F	0.093	0.088	0.146	0.104
G	0.106	0.106	0.164	0.132
H	0.122	0.113	0.166	0.148
I	0.037	0.033	0.096	0.104
J	0.089	0.115	0.091	0.135
K	0.112	0.088	0.145	0.133
L	0.091	0.053	0.101	0.131
M	0.155	0.158	0.152	0.119
N	0.174	0.165	0.137	0.138
O	0.108	0.121	0.123	0.133
P	0.121	0.090	0.154	0.111
R	0.113	0.119	0.155	0.128
S	0.096	0.147	0.110	0.112
T	0.044	0.050	0.128	0.127
U	0.107	0.094	0.124	0.138
V	0.108	0.101	0.128	0.114
W	0.160	0.131	0.149	0.137
X	0.155	0.125	0.134	0.117
Y	0.094	0.096	0.130	0.088
Z	0.085	0.160	0.121	0.139

4. APPLICATIONS AND OUTLOOK

4.1 Discussion

We finally discuss the results obtained from the various analyses performed on the SMS and bistable switch Mechxels for both perceived value change and character replication. In this discussion we also explore the various potential actuation methods and discuss the numerous potential applications of this novel display technology.

4.1.1 SMS Mechxel

The obtained results indicate that the miniaturized Mechxels carry similar value characteristic as their larger counterparts and are successful during the Mechxel-based tessellation of characters. We also demonstrate that the reduction in mechanical pixel size still yields similar changes in color intensity with the histogram analysis, which manifest as perceived changes in color values of that hue; the blue Mechxel in its pop-down state appearing as a more intense shade of blue than in its pop-up state. Using the same systematic process, a sample tessellation of a simple stock image of a globe as can be seen in Figure 4.1 with a height of 25 Mechxels. As for the alphanumeric characters that were rendered, the details of the image are not as resolved compared to the original image. Nevertheless, the image can be easily recognized at a low Mechxel density.

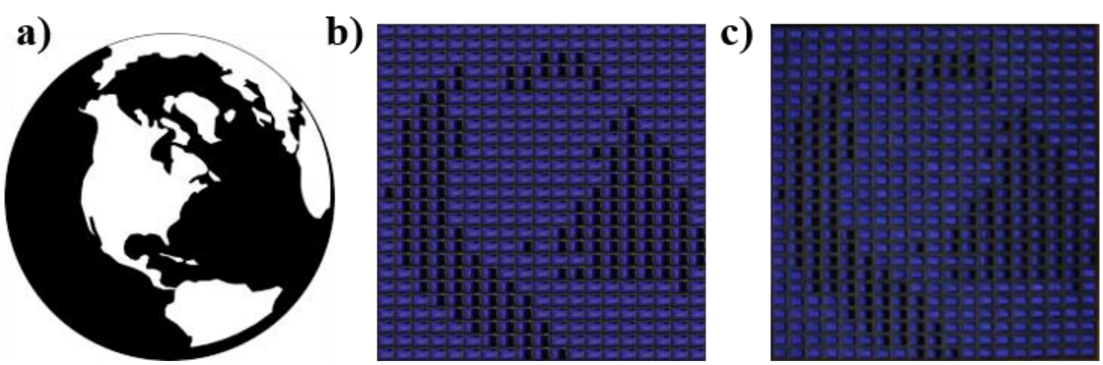

Figure 4.1. a) Stock image of a globe [63]. b) Digitally simulated tessellation of globe image using tessellation program. c) Physical tessellation of globe image.

Even though we observe that the physically tessellated characters are recognizable, compared to the digitally tessellated characters, the tonal values of the physical tessellations are not as homogeneous. This result relates to the minute inconsistencies in printing, causing small variations in deflection when the Mechxels are activated. Despite the mentioned limitations, we demonstrate the possibility of passive, deformation-based color change to resolve characters and images without needing continuous external stimulus, unlike pneumatically [33,34], electronically [5] or mechanically [6–8] actuated structures. Once the Mechxels have been activated and snapped to the required shape, they maintain their deflection with no external input. This process is repeatable and easy to replicate and manufacture. Through simple rearrangements, Mechxels can provide a diverse range of possibilities in display replication and generate aesthetic applications in numerous areas. Within minutes, we can reorganize the Mechxels to resolve a different image.

4.2 Bistable Switch Mechxel

As for the bistable switch Mechxels, with the modifications made to the original switch design, a multistable 5-by-5 grid is successfully implemented capable of reproducing characters in the specified typeface. With a 90.0% match between reference and documented images of the grid and only an 8.8% difference in pixels captured, the images capture the characters that they are supposed to replicate relatively well. As mentioned earlier, if the pixel grid were expanded to accommodate the character “Q” and bold font characters that require a 6-by-6 grid, characters would also be able to be represented with the same Silkscreen typeface. As the entire system of Mechxels are FDM 3D printed, they do not have the resilience for high cycle use. However, this puts forth the proof-of-concept that leverage bistable mechanisms to develop a simple and easily reproducible display system that can be both interactive and potentially actuated through simple mechanical modifications. With simple manipulation, individual Mechxel states can be changed to create a totally different image.

Although the comparative analysis between reference and documented images of characters yielded promising results, non-homogenous lighting caused shadows to be casts onto adjacent tiles resulting in areas that were colored white to be register as gray tones. This affected the overall definition of the tiles when pre-processed in MATLAB. Unlike most state-of-the-art display systems based on light emitters to elucidate characters and images, the Mechxel display depends on surrounding light to illuminate the tiles which inherently affects if the characters are resolved. However, as the human visual system is significantly more complex in comparison to simple image thresholding, a more thorough investigation into both the analysis methods to emulate human perception as well as human surveys on character resolution should be considered.

4.3 Areas for Further Investigation

This research has provided the proof of concept for reproduction of text and images using both purely elastic means through the switchable bistable Mechxels leveraging pre-stress during FDM 3D printing and varied deformation through bistable switch Mechxels. However, there are still avenues that can be further investigated and explored. One avenue calls for a deeper understanding of color change examined through the variance of lighting and viewing angle of the various tessellations created. As illustrated in Figure 3.6b, with a change in documentation angle, the tessellated characters are still remotely visible to the viewer. However, the question remains as to what extent those characters may be recognized leaves room for exploration. To that end, the effect of lighting and color of the tiling also play a role in resolving the images or characters.

Another area that could be examined would be the use of the typeface used for replication. As illustrated in the bistable Mechxels, fonts that not only have variance in stroke thicknesses, but also smooth curves are particularly difficult to represent using the low resolution means of the Mechxels. As such, not only can the scale of both Mechxel designs be explored to continuously push the limits of miniaturization, but an examination of image resolution with increasing Mechxels display size be considered such as increasing the tiling displays to 10-by-10 tiles per character and so on. This should be considered for future investigation as the low-resolution structure of typefaces such as Silkscreen may not be the best for comparison for characters with high similarity such as “O” and “C” which in this instance differs by the state of only one Mechxel. To push the limits of this exploration further, various Serif typefaces can also be used to determine the resolution necessary to resolve these images due their more complex geometry with drastic variances in stroke weight and small flourishes at the end of strokes.

With respect to the manufacturing process, further attention to detail can be given to the tolerances of the manufactured components of each tile. Due to the limitations of FDM 3D printing, which at the best of times still results in minor defects and heavy post-processing requirements, variation in tile dimensions occur often to the detriment of expected deformation after actuation or tile alignment. This results in Mechxels having variations in layer thickness throughout the tile deviating from CAD models or misalignments during assembly that become increasingly apparently when attempting to recreating characters or images. Considerations towards other manufacturing processes such as injection molding, particularly for the switch Mechxels, not only proposes the increase of the bistable switch life [64], but also will minimize postprocessing times and tolerance issues. By leveraging the manufacturing process, modifications such as implementing multistability into individual Mechxels can also be considered to create greater variance in display tonal values and textures.

Finally, as the Mechxel grid analysis was an attempt to evaluate the effectiveness of replicating the characters only with respect to their digital equivalent, no examination of character recognition was conducted. As digital image processing does not always capture what a human observer may perceive, surveying independent viewers is crucial to determine how effective the Mechxels are in reproducing characters and images. Although similar low-resolution character displays have already been used in flip-dot displays [65] showing the human ability to resolve characters, an examination of color variation, display size and distance from the viewer as well as determining differences between characters are all be areas for further investigation to determine the viability of this novel display method.

4.4 Automated and Dynamic Actuation

To further advance the concept of passive color change using SMS Mechxels, we can consider actuation methods mentioned in complementary research areas of the hygroscopic materials [36–38], bio-actuation [66] as well as light reactive materials [67] and SMPs [55]. Although these are slower methods to actuate the proposed idea of SMS Mechxels, occurring over the course of minutes or hours, they are passive modes of the deformation that would allow the perceived value change to require little to no energy for actuation. An example to illustrate this would be the research conducted in hygroscopic materials that has resulted in wood fiber infused 3D printing filament. This hygroscopic material comprised of up to 40% wood fiber content which swells when exposed to humid environments. Although not bistable, using a bilayer structure with a constrain layer and active layup from 3D printing, reversible deformations can be observed similar to that of the SMS Mechxel between its as-manufactured state and pop-up state. Other possible mechanisms to achieve these deformations would include tape springs and bistable composite laminates that exhibit similar shape morphing behavior. As the means of color change resides in the change of perceived area of coloration purely through deformation, any material or metamaterial that can achieve similar deformations with adequate deflections are viable means to create similar visual and textural results.

Pertaining to the bistable switch Mechxels in achieving color change and displays, transition waves [69,70] can be utilized to convert from one visual outcome to the next through the switches' change in state. Transition waves are highly localized waves that change the state of the medium and propagate without dispersion. An example of transitional waves are domino chains which, when tipped, switches the state of each domino from upright to fallen from the start end of the chain. This transition between states also requires less energy than switching multiple switches independently [71]. Preliminary examination utilizing this method of actuation was explored using the setup in Figure 4.2. This setup utilized a larger sized bistable Mechxel in order to better differentiate the onsite and intersite stiffnesses of the switch and spring respectively. Grading was also performed by reducing the thickness of each switch from one end to the other with the purpose of allowing the transition wave to propagate throughout the entire structure without reverting to their initial configuration or stalling midway through state changes [72]. In Figure 4.2b, the drastic change in displacement between 0 and -5mm to under -20mm indicates the snap-through of the Mechxel chain that was connected in sequence with a FDM 3D printed spring. In a transition wave, this snap-through would occur sequentially from the first Mechxel to the last. However, towards the end of the snap-through, we observe that the last Mechxel tile (i.e. 5^{th} Mechxel) finishes its state swap before the 1^{st} to 4^{th} should otherwise not occur in the propagation of a transition wave. Although the results of this transition wave experiment were inconclusive as indicated in Figure 4.2b, it showed great potential for future study in using this actuation method to propagate the state change and thus the color change in the Mechxel display. With careful fine tuning of onsite and intersite spring stiffnesses, propagated transitional waves also have the potential to limit the number of switched states desired and even automatically reverse the bistable Mechxel's state after a stipulated time [72,73]. This method also opens various degrees of electrically independent transformation between various display results such as changes between colors or message displays.

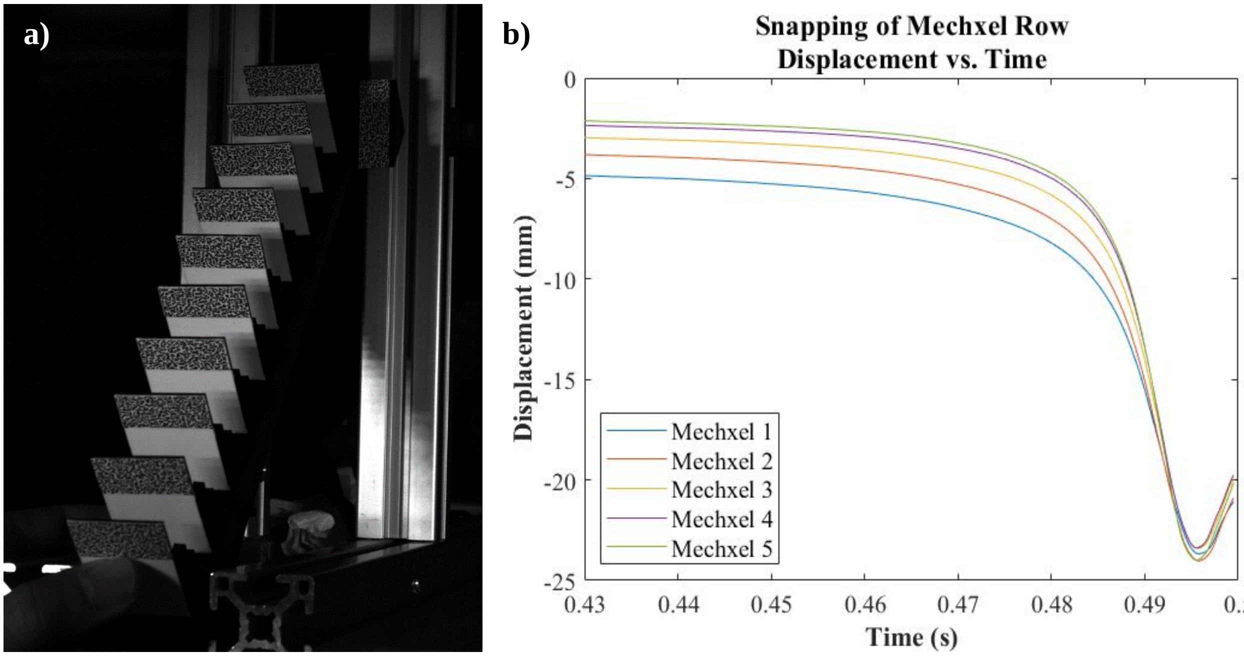

Figure 4.2. a) A single row of Mechxel tiles to examine the viability of state change propagation using transitional waves actuated from the bottom to the top. b) Graph of displacement (mm) vs. time (s) as the central 5 Mechxels are snapped between states. The drastic drop is displacement represents the snap-through with the Mechxels snapping in a staggered manner indicating the potential of a transitional wave being propagated as the state change happens. However, it can be observed that the 4th Mechxel snaps before the 5th.

4.5 Potential Applications

Apart from the potential applications for low-energy displays that carry similar characteristics to flip-dot displays, there are a slew of other practical applications that this color change method can be applied to. Utilizing the change in color from various viewing angles, if miniaturized further, could be applied to adaptive camouflage in military equipment. Such applications would allow the identification of equipment from limited viewing angles while blending into their surroundings from others. Research in the bio-responsive material architectures has already seen deformations similar to that of the SMS Mechxel on body suits which can be tuned to adapt this color changing application. Adaptive solar paneling is also another potential area of application. If material properties in hygroscopic [36–38] or photosensitive [67] materials are utilized to emulate similar material deformations, flexible solar paneling can be adhered to the curvature of the bistable Mechxels and tuned to morph according to preprogrammed environmental conditions. This can allow the optimized collection of solar energy to obtain the maximum intake of sunlight throughout the day through passive angle changes of the solar panels.

Morphing structures are also not alien in architectural research, with many proposed ideas using electromechanically actuated origami structures to assist with adaptive shading design. However, with upcoming bio-inspired research developments leveraging the hygroscopic properties of wood veneers or wood fiber infused filaments [37,38], there is great potential in the Mechxel's integration into interactive architecture where visual texture can be coupled with adaptive, passive color change for both interior and exterior applications.

Beyond the practical applications of low-energy displays, camouflage applications, adaptive energy harvesting and shape morphing architectural systems, aesthetic applications for this technology are limitless. Like the designs constructed by BREAKFAST and various other international installation artists, Mechxels provides two potential interactive installation design methodologies that is accessible to everyone. With its simple model and easy to manufacture and actuate design, Mechxels can easily be recreated and adapted to any future aesthetic concepts for sculptural or installation purposes. Although we have demonstrated two methods of redefining how people may view color change and text and image displays, this method of changing surface color or texture can easily be adapted using other methods of shape morphing technology or structures than enable variance in projected area to potential audiences offering limitless possibilities.

5. CONCLUSIONS

In this dissertation, we leveraged bistability to propose the design of two variations of Mechxels – mechanical pixels, using spatially distributed pre-strain in FDM 3D printing and a bistable switch inspired design to achieve deformation-based color change and also demonstrate their potential to recreate text characters and simple images. The SMS Mechxel takes advantage of the shape memory properties in PLA. Through a bilayer design and curation of extrusion orientation, flat prints can be activated into their stable configurations when exposed to temperatures above their glass transition temperature, resulting a bistable shell. This concept was adapted to be constrained at one edge and surrounded by a rigid ABS frame at limited the deformation to a single edge creating a fast-morphing and easy to actuate "pixel". In order to efficiently replicate text and images, we also created an easy-to-use interface that would determine the number of SMS Mechxels the design characters or images. Finally, we verified the color variation potential and preliminary exploration into recreation of characters through color histogram analysis and character recognition.

This deformation-based display method was also illustrated using bistable switch mechanisms that allowed the projected area of the Mechxel tile that faced the viewer to appear as a square. The design was recreated and modified from an educational model of a four-bar bistable switch mechanism, accommodating other assembly modifications to assist with assembly and replaceability. Switches could then be swapped between states to obstruct the view of the colored tile thereby changing the perceived color between white and black. With a 5-by-5 grid system, it was shown that majority of the alphabetical characters could then be reproduced. Visual comparisons between reference and documented images in using the Silkscreen typeface, also demonstrated the potential viability of using this bistable system to display characters with an almost 90% precision with errors primarily stemming only from variations in lighting considerations and manufacturing tolerance issues. All these issues could be easily resolved through perfecting the manufacturing methods.

In conclusion, Mechxels present the current potential of using 4D printing capabilities to produce dynamic, easily manufactured structures that are easily reproduced with hobbyist 3D printers. Although the size of both Mechxel designs could potentially be reduced further through greater depth of material analysis and understanding. Other potential manufacturing methods such as injection molding and milling could also enhance the robustness of the entire assembled system. With future research, Mechxels can provide an avenue for passive deformation-based color changing displays that actuate based on environmental stimuli. Through simple innovation and creativity, Mechxels offers a new perspective on deformation-based displays and color change methodologies. If viewed through a different lens and way of thinking, various other methods of color change and display technologies can be designed around such deformation-based concepts and material systems, opening the door to limitless design possibilities and potential applications in product and architectural interior and exterior design.

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