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**Andrew Johnson**

Remotely Controlled Curvature on Liquid Crystal Elastomer  
Networks Using Light

**Faculty Sponsor**

Dr. Chenhui Peng



## **Abstract**

Liquid crystal polymer networks are a new and revolutionary field of soft matter physics with a strong application in soft robotics. However, this new genre of soft robotics is not well understood and thus calls for research to be conducted to learn more about its material properties. In this paper we discuss a method of “programming” the movement of macroscopic liquid crystal polymer networks by using photopatterning techniques and inducing the movement of said polymer films by optical means produced by an intense blue (400nm) light. The induced curvature from this light produces results consistent with the Gauss-Bonet theorem of curvature and can be analyzed using the corresponding Euler Characteristic for each handlebody created.

## Introduction

Using liquid crystal elastomers for soft robotics is a method that has been used previously to analyze different forms of motion, such as reproducing that of a caterpillar [1]. studies, this caterpillar-like motion was able to be produced in samples that mimic the actual scale of a real-world caterpillar, thus showing that this locomotion also can be reproduced in macroscopic samples [1]. This caterpillar was made from a liquid crystal elastomer which was then controlled by light [1]. This motion opens the way to many new developments in the fields of soft robotics.

Although the creation of this caterpillar is very important for the field of soft robotics, the method used to “program” the motion of the caterpillar can be difficult to reproduce. There have been recent developments in the methods used to create this programmable pattern, namely photopatterning. This new form of programming allows for many different types of motion to be produced. In this paper, we use a form of photopatterning using SD1 as detailed in a paper by Chenhui Peng [2]. The method of photopatterning using SD1 is the primary method of producing samples in this paper.

While the method of SD1 photopatterning has been studied there is still a need to understand which photopatterns produce which result and how each photopattern can potentially be used in the future. There are many types of photopatterns that have been identified and experimentally produced using focusing a beam of light through a rotating polarizer to produce samples with various alignments [3]. One special feature of using this method is that it converts topology (the differential geometry of an object) into topography (the physical surface of the sample) [3]. This allows us to connect the mathematical theory to the experimental result.

In this paper we use SD1 photopatterns to produce samples with unique topologies, topographies and induced curvatures. Every sample we produced has a unique curvature and all curvatures follow the Gauss-Bonet theorem. Thus, we plan to show that our experimental findings are consistent with the theory guiding them.

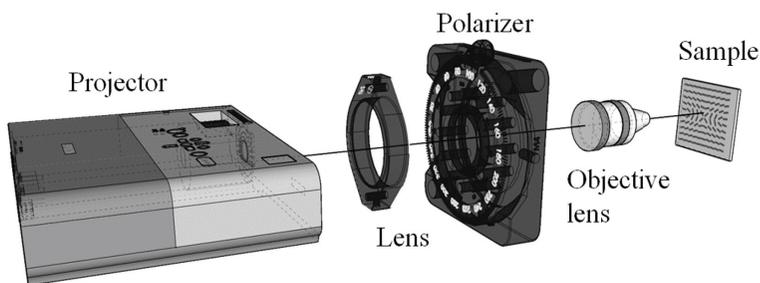
## Methods and Materials

The experimental process began by preparing the sample for testing. This consisted of a 2.5cmx7.5cm glass substrate being cut into 3 equal pieces (2.5cmx2.5cm). Before the substrate was cut it was inspected for any scratches on the surface that would alter the result. Glass substrate found to have no significant amount of damage or dirt was placed in an ultrasonic cleaner for 8 minutes in order to remove minor dust particles on the surface.

The samples were removed and washed thoroughly (on both sides) with tap water to remove any detergent that might still be attached to the substrate. The substrate was then given a thorough rinse on both sides with acetone and then isopropanol. After most of the isopropanol had dripped off the substrate it was placed in an oven at 100° C for a minimum of 20 minutes to evaporate any remaining fluid that present on it. After this time in the oven the substrate was placed in a UV-Ozone cleaner for 5 minutes.

After the substrate was taken out of the UV-Ozone cleaner it coated with photosensitive dye solution. A pipet was used to apply 5-10 drops of the photosensitive solution onto the glass substrate which was then equally spread around the rest of the substrate in a spin coater leaving behind an imperceptibly thin film. At this point, the substrate was photosensitive be handled in a low-light environment while experimenting.

The experimental setup for the study is depicted in Figure 1. It consisted of one laser projector with its beam focused through two lenses to concentrate and maximize the intensity of light produced into a small area for photopatterning purposes. To photopattern the sample, the light beam traveled through a linear polarized film attached to a rotating stage, allowing change in the angle of polarization on the sample. Finally, we had attached two-sided scotch tape to a vertical mount such that the incidence of light was perpendicular to the sample's surface. The amount of exposure per sample depended on criteria such as the pattern desired, and temperature/humidity, and production environment. The common range for photopattern exposure time was 30-120 seconds.

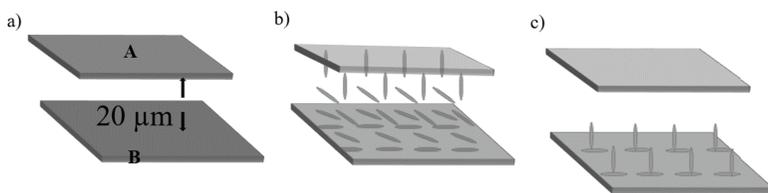


**Figure 1.** Depiction of our photopatterning setup.

After photopatterning had occurred, the sample was tested to confirm a pattern imprinted. To do this we applied 2-3 drops of RM257 liquid crystal solution before it became an elastomer and spun the substrate at 6000RPM in the spin coater to get an even coating. Applying and spin-coating the sample with RM257 is a time sensitive endeavor, needing to be completed in under 10 seconds. This is due to the fact that the RM257 will react with the SD1 film and make the solution thick and viscous, thus unable to produce a uniform film of RM257 on the sample. After successful coating has occurred, we held the substrate up to a background light (such as a ceiling light, desk lamp, etc.) to observe dark regions on the substrate in the shape of the photopattern used. If the observable region was clear, then photopatterning is successful. At this time the sample was placed under a UV-light for 20 minutes to polymerize the RM257 solution that was applied to it.

The sample was then prepared for the addition of the liquid crystal elastomer solution. The solution in question contained RM257, RM105 (both chemicals being the makeup of our LCE), Irgacure-31 photoinitiator (allow the solution to be sensitive to light) and DR1-A (red dye) all thoroughly dissolved in DCME (Solvent). After each chemical has dissolved in solution, the vial containing said solution was placed on a hot plate at 105° C for 1 hour and 30 minutes to evaporate the remaining DCME. The remaining syrup-like liquid is our liquid crystal elastomer solution (LCE solution). When preparing the sample for addition of the LCE solution a very small drop of 20 micrometer UV-activated epoxy spacer was placed in all 4 corners of the sample and then topped with a homeotropically aligned glass substrate (with the aligned face of the original substrate and homeotropically aligned substrate facing each other). At this point the glass “sandwich” was cured under UV-light for 30s-1 min.

The sample was then placed onto a heat-controlled hotplate at 80° C. After reaching 80° C the LCE solution was carefully injected between the two plates until all available space was covered due to capillary action. Once all available space had been filled the sample was brought down to 45° C at a rate of 5° C/min. Once the entire sample had reached this temperature it was then polymerized underneath a UV-light for 30 minutes. The two glass substrates were then carefully separated via razor blade. The three stages of the process can be seen in Figure 2.



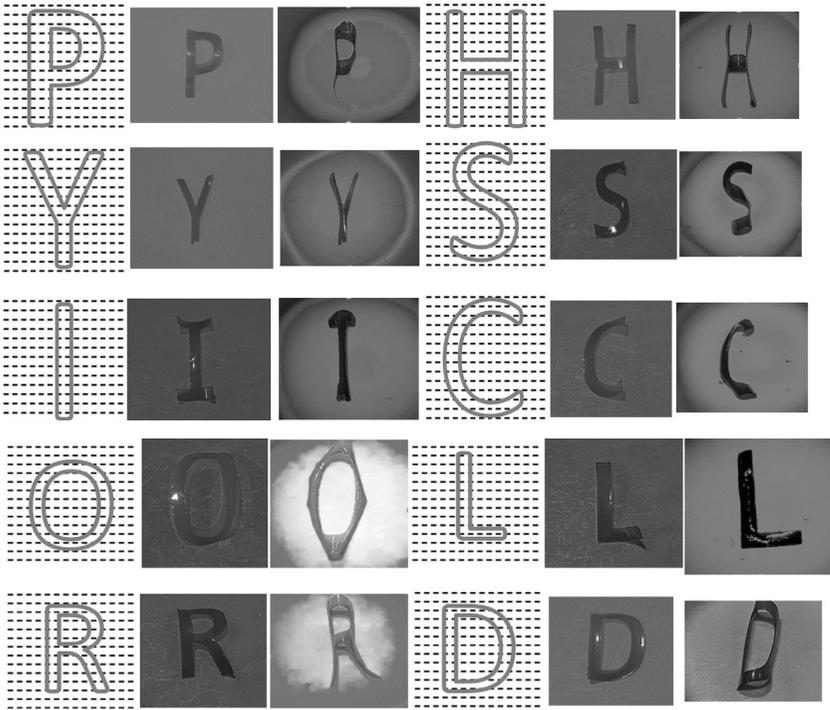
**Figure 2.** Three stages of sample preparation.

In Figure 2, it can be seen that the homeotropically aligned layer was attached to the photopatterned layer (B) using 20-micron spaced epoxy. The LCE solution was then injected between the two plates where the polymer began to align perpendicularly with the homeotropically aligned layer on the top and parallel with the photopatterned layer on the bottom. In the final phase, once polymerization had occurred, the two layers were separated leaving the solid polymer film attached to the photopatterned layer with a homeotropically aligned layer and a photopatterned aligned layer.

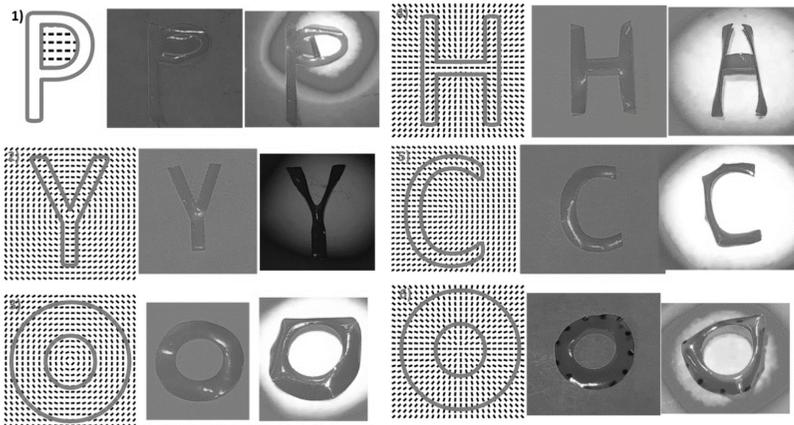
The hardened LCE was then attached to the original substrate instead of the homeotropically aligned substrate. At this point a laser cutter was used to separate the photo patterned LCE film from the film that did not contain any photopattern. The sample was once again placed in the sonicator, for 1-2 minutes to aid in the removal of the sample from the glass substrate. Once removed from the sonicator, tweezers were used to remove the sample from the glass substrate, and placed under a 400nm blue light for analysis.

## Results and Discussion

In total, many different LCE films were created each with a unique patterning and a unique curvature. The first samples were created in the shape of letters that spelled “physics world”. Each letter had its own unique motion and thus created with its own unique curvature. Before creating every letter with a unique movement, we first made every letter having uniform horizontal alignment, as seen in Figure 3. Unfortunately, due to time constrictions, we were unable to complete the entirety of “physics world” but we were able create most of the letters, as seen in Figures 3 and 4. Curvature was successfully induced due to the intense blue light used. The energy of the 400nm blue light was transferred into thermal energy upon interaction with our LCE material and thus induced a phase change, causing the material to expand on one side and contract on the other. Based on this curling motion, and how the photopattern was used to control this curling, we were able to use the 400 nm blue light to remotely control the programmed motion of the soft robots produced.



**Figure 3.** It can be seen that most of the letters in “physics world” with their director field, relaxed form and excited form while underneath the blue light ( $\lambda=460\text{nm}$ ).



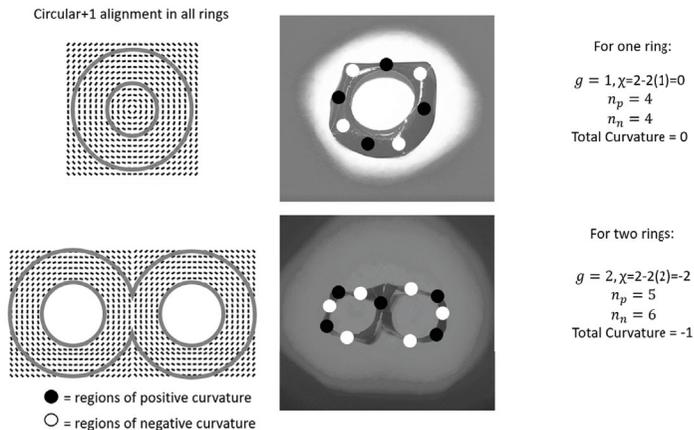
**Figure 4.** On the first sample, letter “P” with uniform alignment only on the space inside the ring in the center. Next, letter “Y” with circular+1 alignment. The third sample, letter “O” (ring) with circular alignment. The fourth sample, Letter “H” with radial+1 alignment. The fifth sample, Letter “C” with +half alignment. Finally, the last sample, Letter “O” (ring) with radial+1 alignment.

After the creation of these letters the focus was shifted to curvature in n-hole handlebodies. Namely, we started with one ring of a certain alignment and analyzed it under the 460nm light and then created a ring of the same dimensions but different alignments to see how the motion would vary between samples. This led to the creation of “ring arrays” containing anywhere from 1 to 5 rings all placed in different patterns to see how each unique curvature would total into the entire curvature of the sample. These were the samples used to create a link between the experimental results and the Gauss-Bonnet theorem. Equation 1 below.

$$\iint_M K dA + \oint_{\partial M} K_g ds = 2\pi\chi$$

**Equation 1.** The Gauss-Bonnet Theorem

The theorem in Equation. 1 cites the Gauss-Bonnet Theorem. Let us dissect this equation term by term. The double integral term is the total curvature of a surface, or the sum of each individual curvature on a surface. The middle term, or the term with the line integral, represents the total turning round boundary. For us, this term is equal to 0 since the integral only applies if there are sharp angles in the boundary of a surface. Since we are only working with rings, our integral becomes zero. On the right side of the equal sign, we see  $2\pi\chi$ , where  $\chi$  is called the Euler characteristic and  $\chi=2-2g$  where  $g$  is the number of holes in the surface. Analyzing four different ring configurations gives us the data shown in Figure 5:



**Figure 5.** Ring Configurations

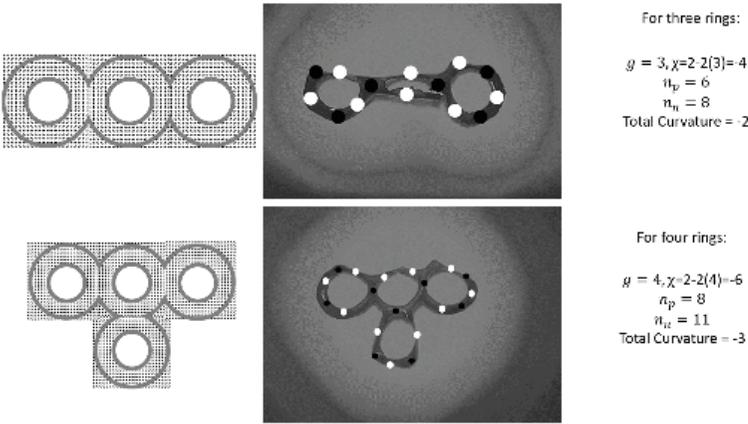


Figure 5. Continued.

Figure 5 depicts 4 different circular+1 ring configurations while they are in their “excited” state under intense light ( $\lambda=460\text{nm}$ ). We can notice through the Total Curvature (tot. curv. =  $n_p - n_n$ , where  $n_p$  is the number of positive curves and  $n_n$  are the number of negative curves) that as the number of holes in a sample ( $g$ ) increase, the total curvature in the sample begins to decrease. The analytical pattern we can see forming is that the total curvature is equal to  $(1-g)4\pi$ . The  $4\pi$  comes from the fact that we are dealing with circles which gives us a circumferential constant we need to include. We can split this equation into  $2(1-g)2\pi = (2-2g)2\pi = 2\pi\chi$ . Since we have shown that the total curvature of each ring array is equal to  $2\pi\chi$ , we have successfully shown that our experiments are consistent with the Gauss-Bonnet theorem.

## Conclusion

In conclusion, this new form of programming soft robots is reproducible and follows the Gauss-Bonnet theorem indicating that theoretical consistency is intact. The results shown that we can program LCE films, based on photopatterns, and can thus create soft robots with abilities from basic folding to more complex motions such as locomotion. We have also demonstrated that by using the SD1 photopatterning method, we are able to create samples that are capable of different forms of motion. We also have demonstrated that our findings are consistent with the Gauss-Bonnet theorem and thus do not deviate from theory.

## Acknowledgements

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