Elastomeric Actuators for Kite-Based Energy Harvesting

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Governor's School of Engineering and Technology 2014

Abstract

This study explores the practicality of using elastomeric actuators to turn a kite. The actuators are used to manipulate a flap which causes the kite to turn; the motion of the kite can then be used to harvest energy. The actuators are fabricated using two elastomeric materials, Ecoflex 00-30 and Mold Star 30, which are shaped using molds constructed with a 3D printer. When inflated, the actuators bend and thus turn the kite flaps. Seven distinct actuator designs were created, tested, and evaluated in this study. The two designs deemed most effective were a string-bound actuator and an origami actuator, an accordion-like, tube-shaped actuator folded from paper and coated with elastomeric material. A group led by Dr. Aaron Mazzeo will utilize the results of this study to continue research into actuators, which may potentially yield a viable design in kite-based high altitude wind energy harvesting.

1. Introduction

Wind is a renewable resource available worldwide for conversion into usable energy. Researchers at the Institute of Electrical and Electronics Engineers have stated that wind could potentially be used to meet the world's energy demand if properly harvested. The main limitation of this renewable power source is in the harvesting technology. Current wind turbines are less efficient and more costly than many other forms of alternative energy. An alternative method of wind energy harvesting now in development involves using kites to take advantage of high altitude wind energy (HAWE).[1] This study analyzed the application of elastomeric actuators in kite-based HAWE harvesting.

2. Background

2.1 Elastomeric Robots

An actuator is a type of motor used for controlling the motion of a system. In this study, actuators are constructed in order to manipulate the flight pattern of a kite. These actuators, which are constructed from elastomeric materials, are characteristic of the field of soft robotics. Soft robotics offers a wide variety of abilities not found in hard robotics. Flexible materials provide multiple degrees of freedom in motion, which can be used to distort robots' forms. This flexibility also allows robots to handle fragile objects, conform to their environments, and distribute pressure evenly without elaborate controls.[2] In addition, soft robotics involves cheaper and lighter materials than hard robotics. Soft robotics allows for the actuator and flap to be attached to the kite without being too heavy for the kite to fly.

2.2 Elastomeric Materials

The elastomers Ecoflex 00-30 and Mold Star 30 were used to create the actuators in this study.

Ecoflex 00-30 is a certified compostable plastic that possesses strong, soft, and elastic properties. Other quantifiable properties, which include tensile strength, tensile stress at 100% elongation, and the elongation at break, are evident through various tests on the material. The tensile stress at 100% elongation is formulated by stretching the material to twice its original size and calculating its change of length measured in meters over the original length in meters. The elongation at break is the percent of the material's original length at breakage. Once cured Ecoflex 00-30 has a tensile strength of 200 psi, tensile stress of 10 psi at 100% elongation, and a 900% elongation at break.[3] Because it is a cured silicone rubber material, Ecoflex must be shaped in a mold and cured; its curing time is approximately four hours.

Mold Star 30 is liquid platinum silicone rubber. Like Ecoflex, it also must be shaped in a mold and cured, and curing time is approximately six hours. After it cures, it has greater resistance to manipulation than Ecoflex does: cured Mold Star 30 has a tensile strength of 420 psi, tensile stress of 96 psi at 100% elongation, and a 339% elongation at break.[4]

Elastomers were chosen for this study because soft materials have never been used to manipulate the flight pattern of a kite used for energy harvesting. These specific elastomers were also chosen due to their unique way of interacting when adhered to each other. When the same forces act on the two materials, Ecoflex deforms at a greater magnitude than Mold Star. If a layer of Ecoflex is attached to a layer of Mold Star, then the greater expansion of Ecoflex causes the two layers to curve. The Ecoflex layer becomes the outer layer of the curve. As both materials expand more greatly, the combined layers bend more; this phenomenon is the primary cause of the bending motion in the actuators.

2.3 Physics of Flight

The focus of the design of the actuator and hinge was to optimize control of the kite's flight path. To successfully fly a kite, the forces of drag, lift, and gravity must be kept in balance. As the kite flies, the air is split and either flows over or under the kite's wings. The air that flows over the top of the kite creates an area of low pressure at the back of the kite, which then creates a vacuum that pulls up; this phenomenon is aptly called backwards pull. The air that flows beneath the kite provides the upwards pressure, which is the lift. The drag is the wind resistance from the kite and the tail, and can also be increased if there is turbulence behind the kite. Gravity is the downward force of the Earth's mass pulling on the mass of the kite. If all of these forces; lift, drag, and gravity; are balanced at the center of the kite where the rods cross, then the kite will fly successfully.[5]

The kite, when unbalanced, can rotate in all three degrees of rotation: roll, pitch, and yaw. Yaw is the rotation about the axis that runs perpendicular to the ground. Pitch is the rotation about the axis that runs from wing tip to wing tip. Rotation about this axis will cause the kite to tip forward or backwards. Roll is the rotation about the axis that runs from the front of the kite to the tail.[6] Roll is the aircraft principal axis that this study will be manipulating to fly the kite in an infinity shape.

2.4 Kite-Based HAWE

Kite-based high altitude wind energy harvesting involves the turning of a kite in an infinity-shaped path, which powers a generator on the ground. The kites' maneuverability and ability to fly at higher altitudes makes it possible to take advantage of the continuous and abundant power of high altitude winds. Kites also have several advantages over conventional wind towers. The kites are less expensive than wind towers, for they are made from cheaper materials and require minimal maintenance. Additionally, kite-based HAWE involves easier production and greater efficiency than conventional wind towers because rotor blades are complicated to manufacture and vortex drag lowers the amount of energy that can be harvested.[7]

3. Experimental Design and Procedure

Actuators were created with elastomeric materials set in 3D printed molds. Bound actuators and origami actuators were two efforts to improve efficiency of actuation and durability of the actuators by minimizing unnecessary lateral expansion, which inhibits longitudinal expansion and weakens the walls of the actuators. Several non-elastomeric materials, such as string, rubber bands, and paper, were incorporated into the composition of the actuators as bindings. Paper was also used to form an origami foundational structure, or "skeleton," on which some actuators were formed. The actuators were then each inflated, and both observational and quantitative data were collected to determine the most fitting actuator designs for the applications of this project.

3.1 Fabrication and Actuation

A basic actuator was fabricated from one layer of Ecoflex 00-30 material attached to one layer of Mold Star 30 material, with one or more air channels between them. In order to create the Ecoflex layer, an amount of component A was combined with the same amount of component B and stirred together. The resulting mixture was then placed into a sealed chamber attached to a vacuum pump, eliminating any air bubbles that may have formed during the mixing process. The Ecoflex was then poured into a 3D printed mold provided by the Mazzeo group and allowed to rest on a flat surface so that it would cure completely level.

A layer of Mold Star material was created with a similar process: the same amount of mixtures A and B were mixed together and placed into a sealed vacuum chamber to remove air bubbles. The Mold Star was poured into a separate 3D printed PLA mold, similarly designed by the Mazzeo group, and allowed to cure. However, once it was partially cured, approximately 20 minutes later, the cured Ecoflex layer was removed from its mold and placed on top of the Mold Star layer. The Mold Star component of the actuator would adhere to the Ecoflex component upon fully curing.

To create a bound (fiber reinforced) actuator, a basic straight actuator was first produced. A selected binding material, such as string, was wound around the actuator tightly, leaving very small gaps. The wrapped actuator was then placed in a shell mold slightly larger than the basic straight actuator that was filled with the Ecoflex mixture. Once completely cured, the Ecoflex would form a thin layer covering the binding material and sealing the structure together.

An alternative type of actuator, the origami actuator, was also explored. It was a tube folded from paper with one of two accordion-like patterns and coated with Ecoflex material. Several methods had to be explored to coat the actuator because there were many difficulties in applying the coating evenly and thoroughly. The Ecoflex was directly poured onto the actuator, painted onto the actuator with a tongue depressor, or poured into a cylindrical mold in which the actuator could be submerged. Once the Ecoflex coating was allowed to cure, circular caps made from either Ecoflex or balsa wood were attached to the ends of the actuator.

For actuation, a small hole was created in one end of the actuator that connected to the actuator's primary air channel. One end of a narrow tube was inserted into the channel, and the opposite end of the tube was connected to a pneumatic device, such as a syringe or an air pump. The syringe was used to test whether a newly-fabricated actuator functioned; an air pump was used when testing the properties and characteristics of an actuator. With the latter method of actuation, internal pressure was always apparent and could be increased deliberately to facilitate measurements.

3.2 Mold and Hinge Design

In order to shape the Ecoflex and Mold Star material into components of the actuators, both elastomeric materials were poured into molds before curing. The molds had been designed with the computer-aided design (CAD) software SolidWorks and 3D printed by the Mazzeo group prior to this study. By changing the mold in which an actuator is formed, the fragility, durability, flexibility, and efficiency of the actuator are modified.

Hinge-like pivots were also created with SolidWorks and 3D printed. The hinges were intended to act as a way to better attach the actuators to flaps on the kite, which would bend the kite's wings and cause the kite to turn. The hinges could more easily bend the flaps than the actuators could alone because they occupied and manipulated larger sections of the flaps.

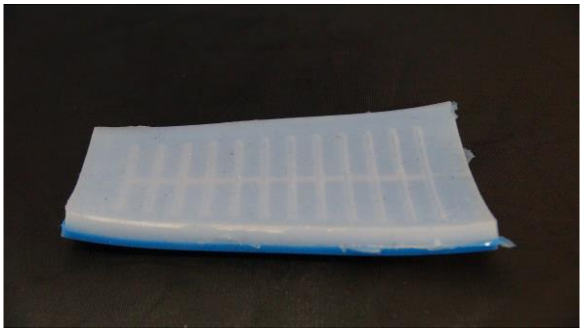
For both the molds and the hinges, parts were created using Fused Deposition Modeling. In this particular case, PLA (polylactic acid) made up the filament used to create the parts. Since the 3D printer used for this research cannot print interlocking pieces, the door hinge pieces and the two pieces needed for the mold of the actuator top needed to be printed separately and assembled later.

See Appendix A for hinge designs and Appendix B and C for mold designs.

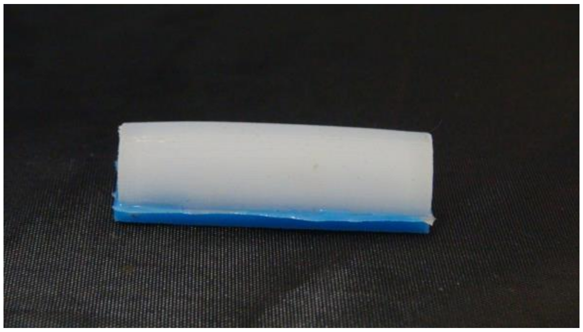
3.3 Actuator Design

3.3.1 Material Experimentation

The Mazzeo group had previously created three basic actuators before the start of this project. The first actuator was flat, and air channels were oriented in a spine-like structure throughout the actuator. The actuator was attached to a flap on the kite and would directly bend the flap when it was inflated. The second design, created by undergraduate students with Dr. Mazzeo, was an actuator from a previous, unrelated study. The actuator had a top component that resembled a hollow cylinder bisected lengthwise, with semicircular ends. The top was then attached to a flat bottom component composed of Mold Star to create a hollow air channel inside the actuator. The third design was similar to the second design, but the lateral surface was ridged instead of smooth. The ridges were modeled from a sine curve so that they could more easily inflate with air.



Original flat actuator. Air channels are oriented in a spine-like pattern throughout the actuator.



Straight actuator. A single air channel runs through the actuator in the longitudinal direction.

Sine actuator. Ridges along the top of the actuator allow the actuator to expand more easily in the longitudinal direction.

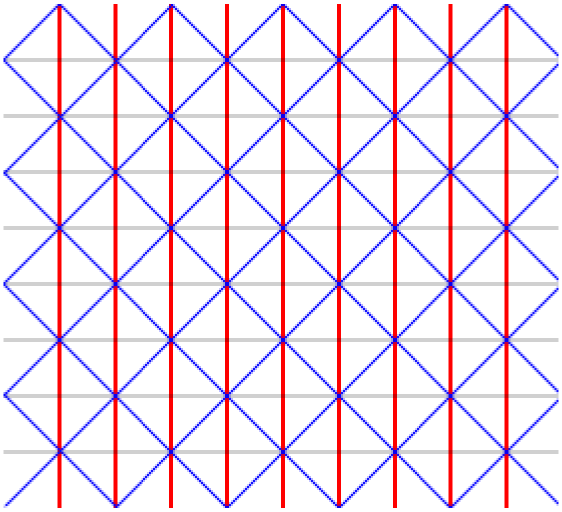
The next modification made by the group involved the use of string as a binding material on the straight actuator. This was done to constrict lateral expansion and to improve longitudinal expansion.

To continue the research of the Mazzeo group, the string bound actuator design was first tested. Rubber bands and strips of paper were then also conceived as binding materials, and the resulting actuators were tested as well and compared to the original string and straight actuator designs. The final direction explored deviated greatly from the standard actuator design through the use of folded paper, or origami. Ecoflex coated the paper and was intended to strengthen the walls of the actuator and prevent air leakage. However, elastic properties of the actuator were lost.

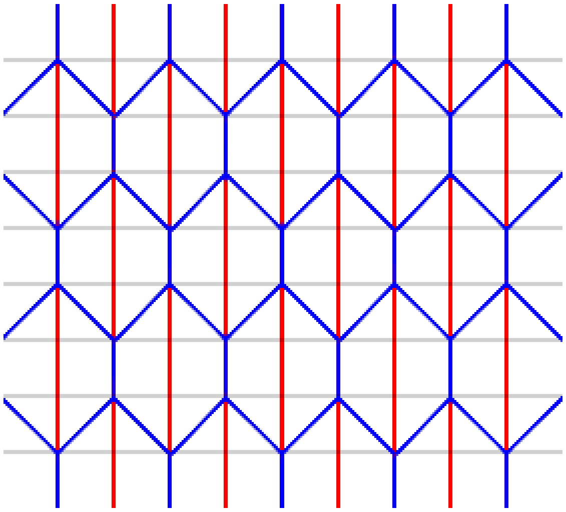
3.3.2 Origami

The sine actuator created by the Mazzeo group incorporated an accordion pattern that allowed the actuator to expand and bend at great magnitudes with very subtle changes in air pressure. This drastic expansion caused the elastomeric material to stretch greatly as well, severely weakening it and increasing the risk of breakage in the actuator. It was suggested by a mentor of this project, Ke Yang, that folded paper, or origami, could be explored as a possible material in constructing actuators. A group at Harvard University, led by Dr. George Whitesides, created actuators consisting of paper coated in Ecoflex material. Although the paper coated in Ecoflex 00-30 did not have the strong elastic properties of Ecoflex itself, it was much more durable than the pure Ecoflex 00-30 designs.[11] An actuator with an accordion pattern did not have to be very elastic to expand and contract greatly, because of its unique tube shape. Therefore, paper folded into such a pattern and covered in Ecoflex appeared to be sufficient.

Two folding patterns were created in order to construct origami actuators. The first was formed from a grid-like pattern of horizontal folds and folds approximately 45 and 135 degrees from the horizontal. The pattern collapsed into a shape resembling a square prism, with accordion-like folds on its lateral faces. The second was a similar pattern, with additional horizontal folds placed between the alternating diagonal folds of the square prism-like pattern such that the space within the actuator was much larger.



Square prism-like crease pattern. Blue lines represent mountain folds. Red lines represent valley folds.



Octagonal prism-like crease pattern.

In addition, three methods mentioned before were used to coat the origami actuators in Ecoflex 00-30. Of these methods, the most effective procedure to coat the origami was to paint the Ecoflex on the folded paper in multiple layers, to seal any air leaks in the paper. The origami would be folded into the proper shape, coated, and left to dry in a semi-compressed state. However, this procedure had to be repeated many times before all leaks were sealed.

Unlike the other actuator designs, all origami actuator designs expanded linearly and did not bend. However, because the hinges could only rotate about a pivot, the expansion of a linear actuator attached to a hinge would cause the hinge, and thus the flap to which it was attached, to bend. If one side of an origami actuator was restricted from expanding, such as with glue or Mold Star, the origami actuator itself would bend in a manner similar to the other actuators tested.

4. Results and Discussion

Two types of pneumatic actuators, bound actuators and origami actuators, were created in this study. Of the bound actuators, the string-bound actuator bent with the quickest and most consistent rate. The rubber band-bound actuator bent somewhat consistently, but the rubber bands increasingly resisted the expansion of the actuator as inflation continued. The Ecoflex shell also could not cure properly or adhere to the rubber bands, even after multiple trials, causing breakage problems in the actuator. Finally, the paper-bound design could not bend as much as the other two bound actuators and bent at a very slow rate. Of the two origami designs that were finally considered, the cylindrical mold design was very resistant to actuation, but the design that had been painted with Ecoflex inflated very easily with small changes in air pressure. Both designs were riddled with leakage problems, and the painted design had to be submitted to multiple coatings before use.

4.1 Pressure Testing: Inflation Over Time

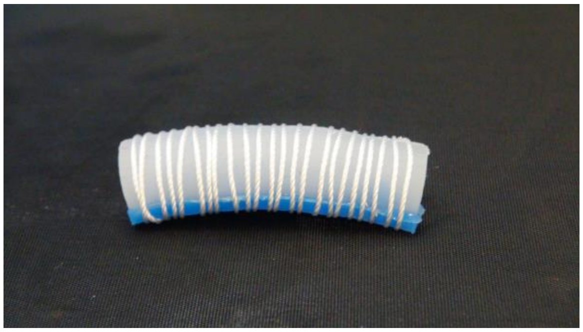
To test the effectiveness of each actuator, pressure tests were conducted. These tests measured the respective inflation rates of each actuator design. Each actuator was connected to an air pump, and the valve of the air pump was slowly opened until the pressure gauge reached 2 psi. The pressure was maintained at that value, and once the actuator inflated to a 90 degree angle, the valve was shut off. To analyze the pressure tests, still frames of each video were individually analyzed, and the magnitude of the angle of inflation at each second was recorded. The slope of the graph represents the rate of change of that angle over time.

4.2 String-Bound Actuator

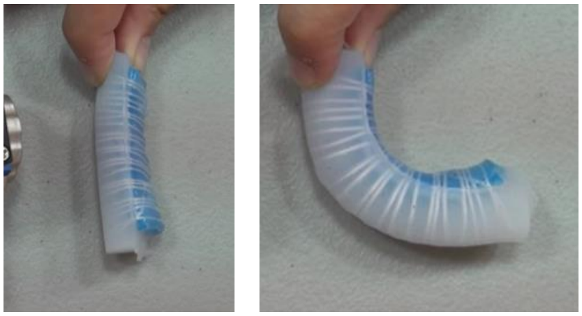
The string actuator was the first of the three bounded actuators created. The string acted as a restrictor to bind the actuator, forcing it to elongate more in the longitudinal direction. The string, when tested, did manipulate the actuator into a more usable movement, but after several tests, it became apparent that the string was constricting the actuator too much. The string was cutting into the Ecoflex 00-30 shell and top, creating weak points and rips in the actuator wall. It was also apparent that, if the space between each loop of string around the actuator was too wide, the actuator wall would push the string out of the way and create a "bubble," or a pocket where there was an abnormally great amount of expansion. This was a major problem due to the added stress on the bubbled section of the actuator wall. The bubble also decreased efficiency and hindered the actuator from bending by allowing the actuator to expand laterally instead of longitudinally. However, if the space between each loop of string around the actuator was too small, the actuator could not inflate enough to be usable on the kite.

When tested for inflation rate, this actuator appeared to follow a linear trend very closely and bent at a near-constant rate. It was also able to reach angles of further than 90 degrees, allowing for flexibility in use (Appendix D, Figure 1). The string actuator was found to have the ideal balance between support and flexibility. This design, when properly constructed, is one of the most promising designs created by this project.

See Appendix D, Figure 1 for a data table and graph describing the inflation of the string-bound actuator over time.



String-bound actuator.



String-bound actuator. Left: just prior to actuation. Right: fully actuated.

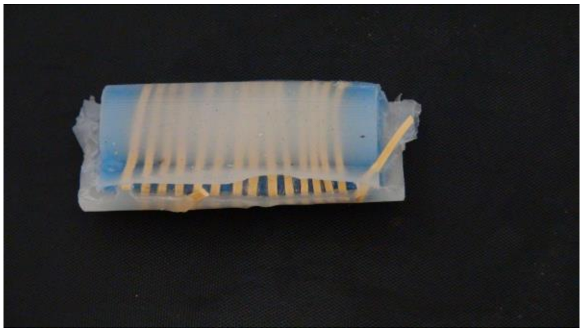
4.3 Rubber Band-Bound Actuator

When creating the rubber band-bound actuator, problems arose that made the fabrication difficult. For instance, the

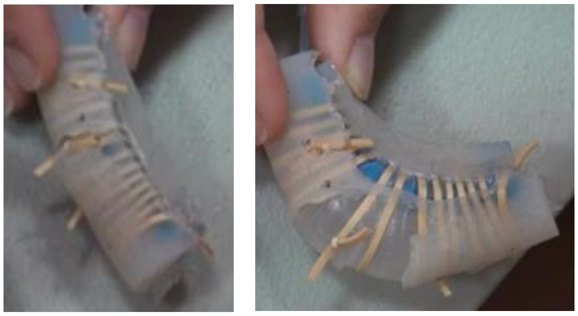
Ecoflex 00-30 did not adhere to the rubber bands, which caused the Ecoflex 00-30 shell to deform and not properly cure. At this point, it is unclear why the two materials did not adhere, but it is possible that the two rubber substances chemically interacted with each other, hindering the curing process.

The improper curing caused the rubber bands to slide during inflation. Several attempts to create the rubber band-bound actuator failed. However, the rate at which the rubber band-bound actuator was inflated could still be observed, and a trend of decreasing inflation with sporadic bouts of increasing inflation was evident. This actuator was also able to easily flex to a 90 degree angle without signs of breakage (Appendix D, Figure 2). Errors may have occurred when attaching the rubber bands to the actuator since there were imperfections that may have caused sudden increases in inflation. Further trials would determine a more precise trend in inflation rate.

See Appendix D, Figure 2 for a data table and graph describing the inflation of the rubber band-bound actuator over time.



Rubber band-bound actuator. Improper curing caused the rubber bands to slide.

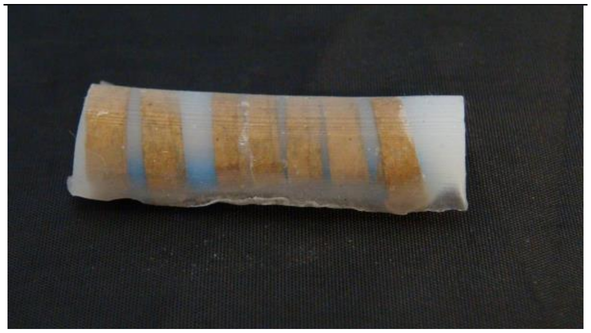


Rubber band-bound actuator. Left: just prior to actuation. Right: fully actuated.

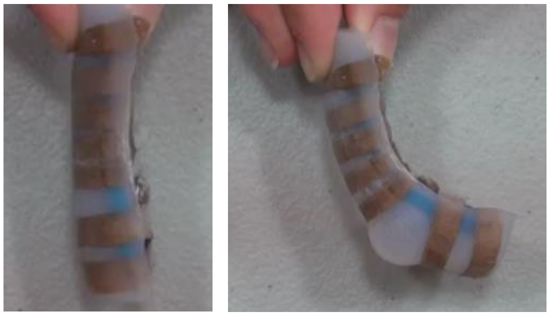
4.4 Paper-Bound Actuator

The paper-bound design was created in hopes of improving the string-bound design. To reduce the damage on the shell and top of the actuator wall during inflation, wider paper strips were used in place of the string. Paper was cut into strips and wrapped around the actuator, with small gaps left between the strips. It seemed that the paper would still be able to constrict the longitudinal movement without causing as much damage because the strips of paper have a larger surface area than the string. However, due to the increase in surface area, the paper constricted the actuator too much and left too few gaps for the actuator to expand. As a result, the actuator was not able to inflate at an angle at a sufficient magnitude.

See Appendix D, Figure 3 for a data table and graph describing the inflation of the paper-bound actuator over time



Paper-bound actuator. The strips used were too wide and inhibited inflation.



Paper-bound actuator. Left: just prior to actuation. Right: fully actuated.

4.5 Origami Actuators

The concept of a functioning origami actuator proved difficult to realize since many of the attempts to construct an origami actuator were unreliable and prone to leakage problems. However, the origami actuator was ultimately one of the two most promising designs that arose from this study.

The leakage issues stemmed from the application of the Ecoflex 00-30 onto the outer surface of the actuators. The Ecoflex 00-30 coating was intended to seal the minute holes and small tears in the origami. Each of the three application methods, however, were flawed. When the Ecoflex was poured on the actuators, the Ecoflex dripped down to one side of each actuator before it completely cured, and only half of each actuator was adequately covered in Ecoflex. The Ecoflex also easily peeled off of the paper, causing air to leak out when inflated. When the Ecoflex was painted onto the actuators, the Ecoflex still slid off much of the actuator, and several areas were not painted because the actuator was partially compressed during application. Eventually, the origami actuator was sealed completely, but only after many applications of Ecoflex.

Octagonal prism-like origami actuator painted with Ecoflex. The balsa wood caps have not yet been attached.

When the origami actuator was submerged in a cylindrical mold filled with Ecoflex, the Ecoflex coating was even after one attempt, but the coating was very thick and resisted expansion during actuation. The resulting actuator became much larger and heavier than the other actuators, and was not practical to place on a kite. Air bubbles also created large gaps that were potential sources of leakage and breakage problems.

Octagonal prism-like origami actuator, submerged in Ecoflex. Air bubbles caused large holes that could severely weaken the actuator.

Although the origami actuator was a linear actuator and could not be compared to the bound actuators with the air pump test, it was observed that the origami actuator functioned effectively and efficiently when actuated despite difficulties in its production.

5. Conclusion

High altitude wind energy harvesting can be made feasible using kites as a means to reach the continuous strong and steady winds in the upper layers of the atmosphere. To control such kites, actuators made of elastomeric material can bend the kites’ wings at varying magnitudes with changes in air pressure. Elastomeric actuators are a practical means of turning energy-harvesting kites because they are relatively strong, very lightweight, and composed of inexpensive materials.

Of the seven actuators designed during this study, the most effective designs were a straight-sided, tube-shaped actuator bound in string and an accordion-like, tube-shaped actuator folded from paper and coated with elastomeric material. Both are fairly durable and expand with only small changes in air pressure. On the other hand, actuation of the other three designs was not as successful. The tension of the binding on the rubber band actuator, wideness of the strips on the paper-bound actuator, and thickness of the Ecoflex coating on the origami actuator all hindered expansion. In addition, the submerged origami actuator and the rubber band actuator experienced problems during formulation, such as large air bubbles and improper curing, that would severely weaken the material and lead to breakage problems. All three of those designs are thus not practical to be used on a kite. However, the string-bound actuator and painted origami actuator are clearly not yet ready for industrial applications, and the Mazzeo group will continue to research improvements upon the actuator designs to make them sufficiently effective, efficient, and durable, with the intention of creating working prototypes to test in the field. Their work will also include programming the kite’s flight path. The overarching goal of this extended research is to refine the kite design for wide scale energy production such that it can be produced for frequent commercial and personal use as a sustainable and renewable energy source.

Acknowledgements

The discoveries derived from this project are due to the help of many important people. Without their assistance, this project would not have been possible. Dr. Aaron Mazzeo is a professor at Rutgers University who oversaw the research done for this project. The authors are grateful for his continued support and his allowance for the use of his materials as well as his lab.

As a Residential Teaching Assistant, Alex Hobbs is a student at Rutgers who has guided the authors along the path necessary for the completion of the research. He has assisted by providing helpful insight along the way. He has also spent many hours in the lab with the authors offering encouragement as well as vital feedback. Much credit also goes to the mentors and workers in Dr. Mazzeo's lab. They have spent time guiding and instructing the authors as well. Ke Yang is a graduate student at Rutgers University who was very helpful in the process of implementing ideas. His intellectual advice paved the way for more ideas to be initiated by the authors. He was also responsible for ensuring that the actuators created were as accurate as possible. Jingjin Xie, also a graduate student, has contributed by providing instruction about the proper way to use the elastomeric materials. He spent time making sure that the experimental design of the project was efficient. Chen Yang is a graduate student who has provided a great amount of input into this project. He advised the authors about using the SolidWorks program while including methods for proper 3D printing technique. Rutgers School of Engineering would also like to be recognized for granting governor's school students the opportunity to use the lab and equipment required to further study and design actuators. There are also many people whose dedication and commitment have made this program possible. Jean Patrick Antoine has devoted time and energy into ensuring that no Governor's School student was limited in their areas of research. His dedication to the program is admirable. The authors also recognize him for his insightful feedback and suggestions that are also greatly appreciated. A special thanks goes to Dr. Ilene Rosen who is the director of the Governor's School of Engineering and Technology. The authors are thankful for this opportunity to expand their knowledge and grow. The State of New Jersey, Morgan Stanley, Lockheed Martin, Silverline Windows, South Jersey Industries, Inc., The Provident Bank Foundation, and Novo Nordisk would also like to be recognized for sponsoring the GSET program. Their assistance has made this program possible.

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Appendix A

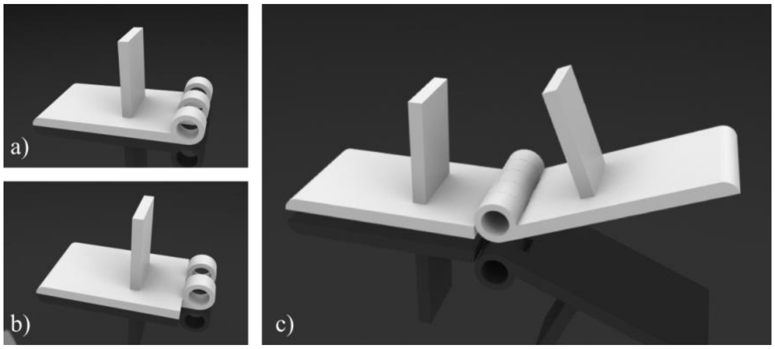


Figure 1: The two parts above (a and b) were combined to create the hinge (c) to which the actuator will be attached.

Appendix B

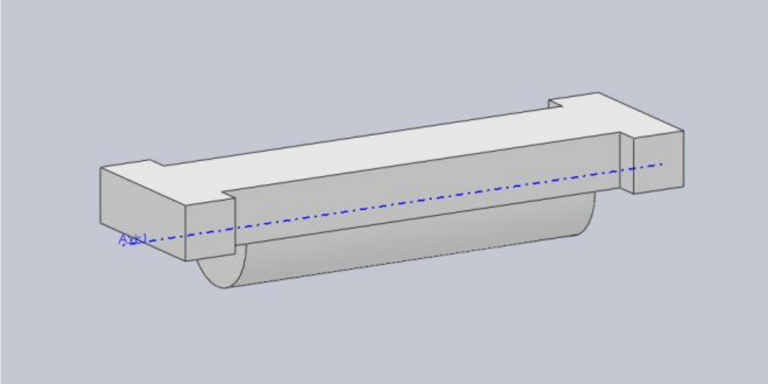


Figure 1: The insert added to the mold of the straight and bounded actuators to form the hollow tube within the actuator.

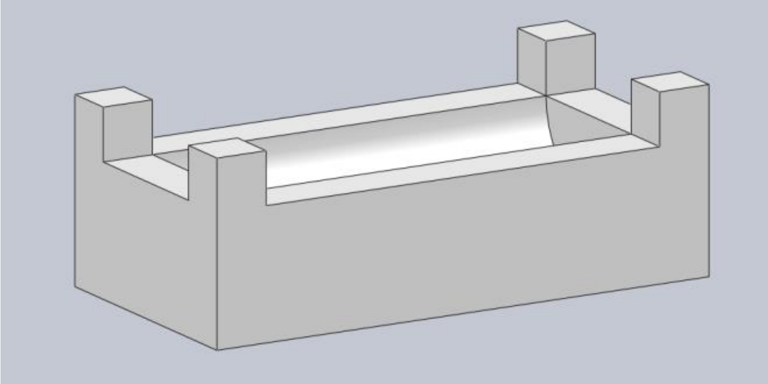


Figure 2: The top mold for the straight and bounded actuators.

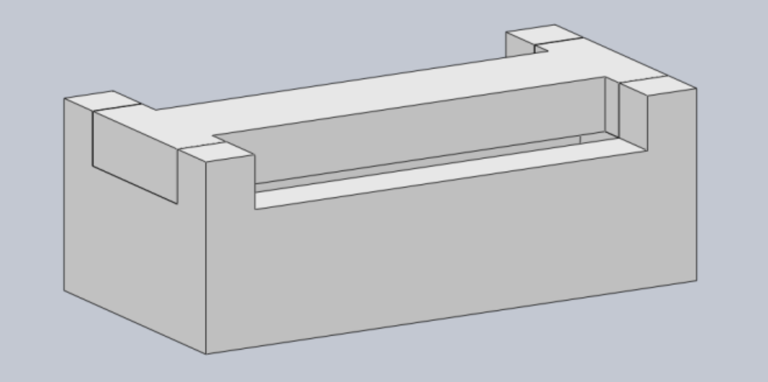


Figure 3: The assembly of the top mold and the top mold insert used to create the top component of the straight and bounded actuators.

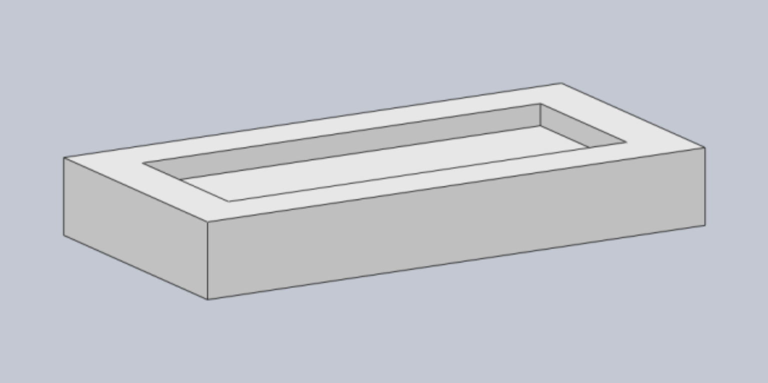


Figure 4: The base of the straight and bounded actuators.

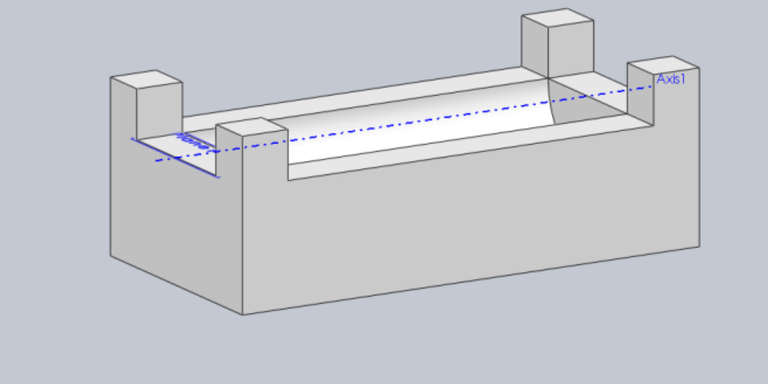


Figure 5: The mold used to create the shell covering the binding of the bound actuators.

Appendix C

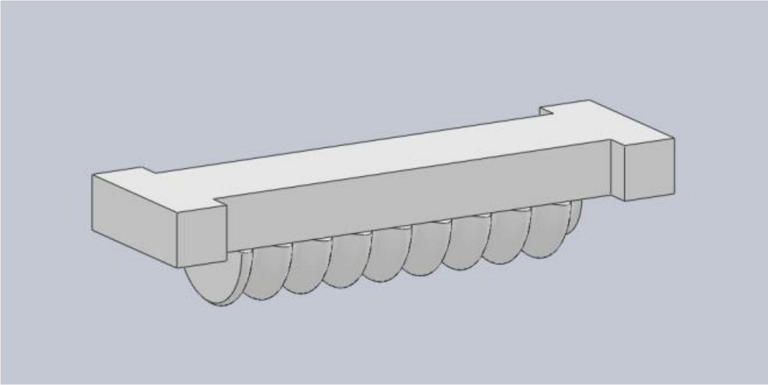


Figure 1: The insert added to the mold of the sine actuator to form the hollow ridges within the actuator.

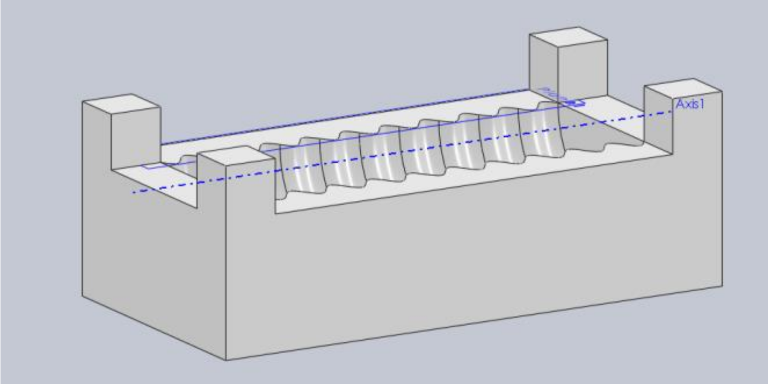


Figure 2: The top mold for the sine actuator.

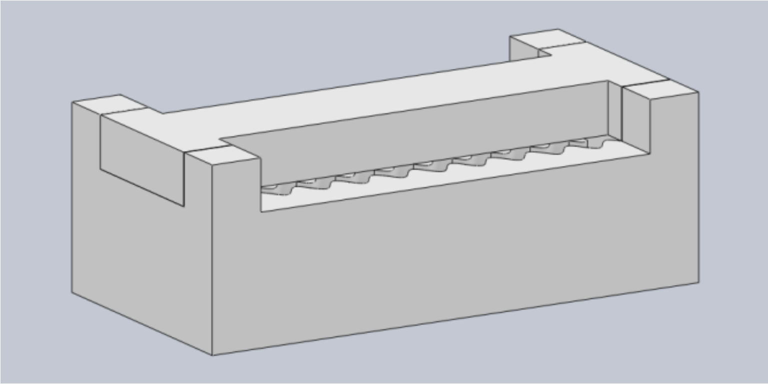


Figure 3: The assembly of the sine mold and the sine mold insert used to create the top of the sine actuator.

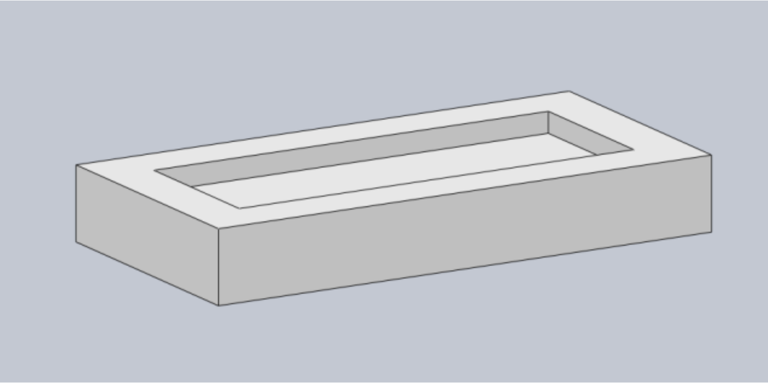
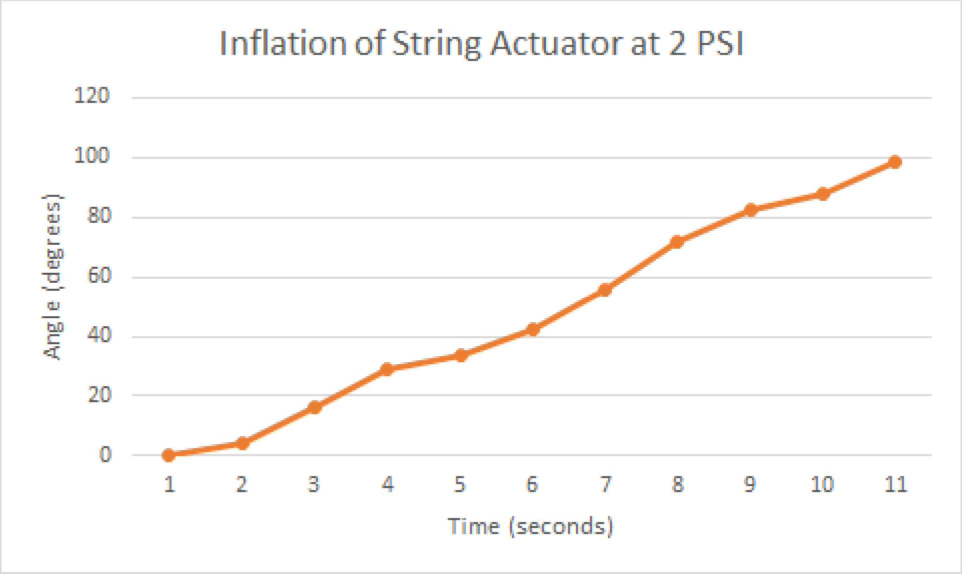
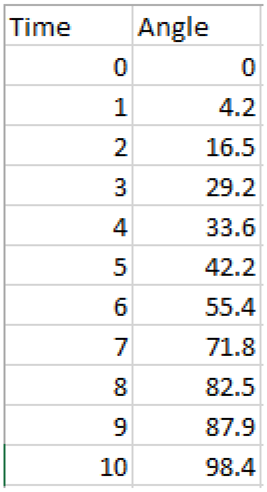


Figure 4: The base mold of the sine actuator.

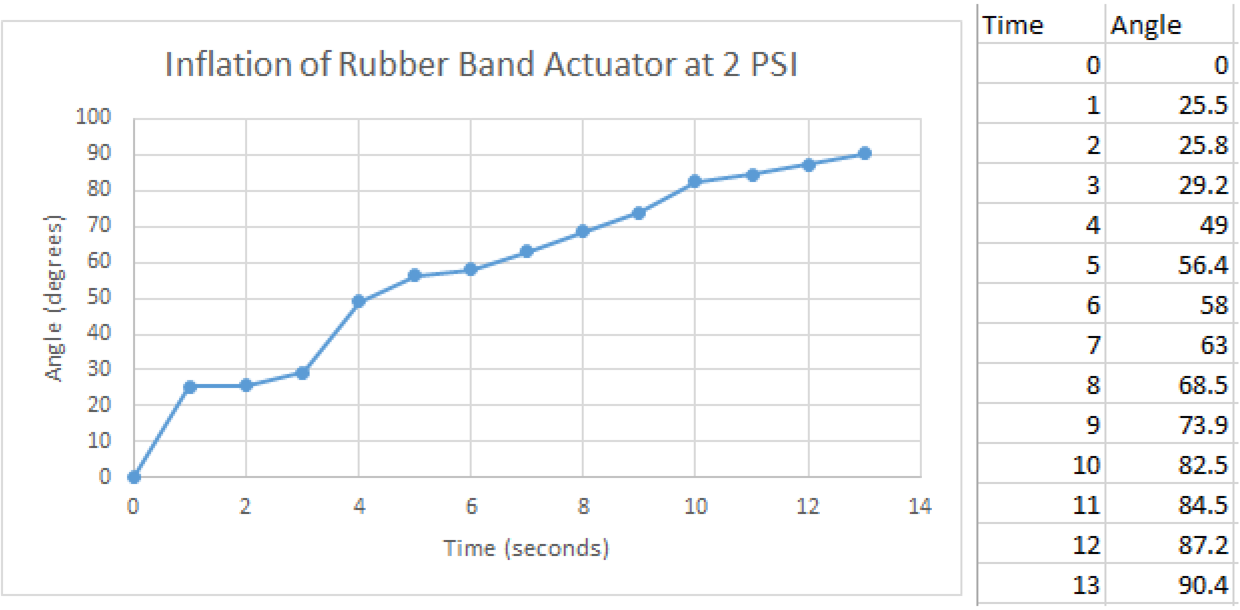
Appendix D





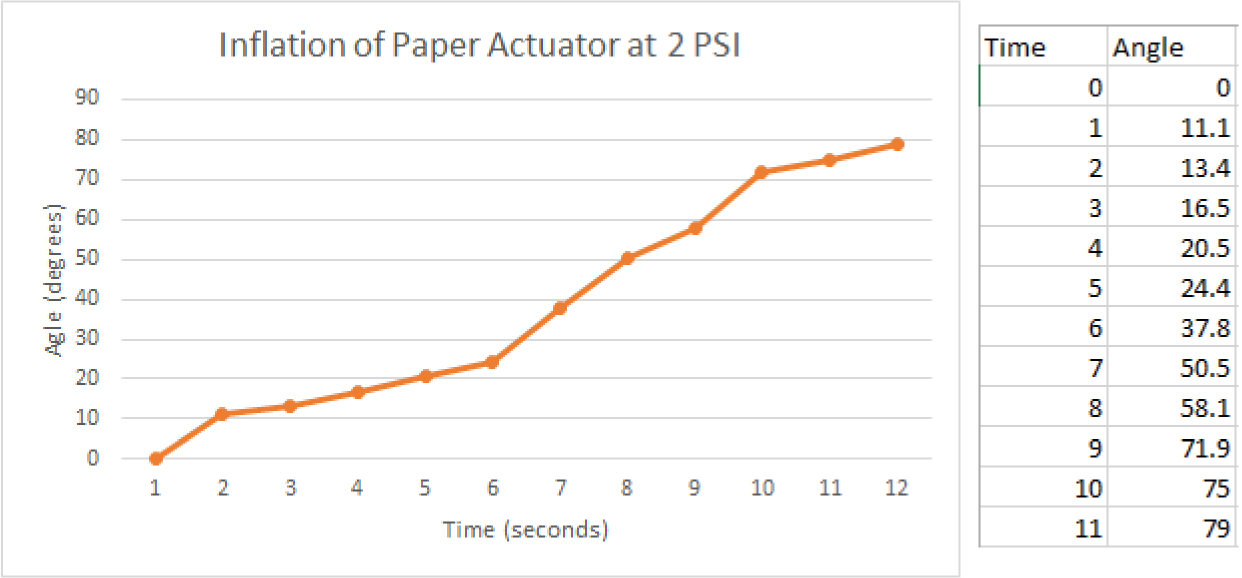
Time	Angle
0	0
1	4.2
2	16.5
3	29.2
4	33.6
5	42.2
6	55.4
7	71.8
8	82.5
9	87.9
10	98.4

Figure 1: Graph of the inflation of the string actuator.



Time	Angle
0	0
1	25.5
2	25.8
3	29.2
4	49
5	56.4
6	58
7	63
8	68.5
9	73.9
10	82.5
11	84.5
12	87.2
13	90.4

Figure 2: Graph of the inflation of the rubber band-bound actuator.



Time	Angle
0	0
1	11.1
2	13.4
3	16.5
4	20.5
5	24.4
6	37.8
7	50.5
8	58.1
9	71.9
10	75
11	79

Figure 3: Graph of the inflation of the paper-bound actuator.