Achieving Control with Mechanical Mechanism

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Abstract Known methods of creating low cost, easy-to-fabricate paper robots require electrical control. In this work, we propose a method of control using a purely mechanical oscillator, called the mechanical logic. Similar to a simple electrical oscillator, it can execute its clocking functions by providing an oscillating electrical signal to a duo-state switch. First, a constant-current power source induces contraction in one supercoiled polymer (SCP) actuator. This contraction enables a bistable beam to switch states, allowing the completion of one circuitry and opening another, with the closed circuit restarting the contraction. We observe repeated pulling of the bistable beam in opposite directions, leading to periodic oscillatory motion. An analysis of temperature and current trends indicate that the oscillator oscillates with an average period of around 3.8 s, thus providing evidence for mechanical control of current oscillation.

1 Introduction

In this research, we would like to replace traditional micro-controller with a less complex mechanical, clocking device. Simplicity allows us to better integrate such clocking device into robots that are designed to be simple enough so that the general community can understand. In order to create this device, we first try to achieve repeatable oscillations on a mechanical device known as the mechanical logic. This mechanical device consists of an actuator, a bistable beam for control of binary information, and a constant-current power supply. With this mechanical logic, we have successfully recorded four complete oscillations, indicating that this oscillation motion is repeatable.

In particular, we define each oscillation as a contraction and a relaxation of the actuator due to heating provided by the current and cooling by fan. The average period of oscillations is measured to be (3.8 ± 0.8) s. This period is a significant balance between sufficient cooling of one actuator and heating of another.

We draw several conclusions from this work

1. The ideal SCP actuator is found using a testing system. We found that an increase of weight we are able to apply to the SCP actuator during fabrication process does not increase the strain of the material, rather it increases the contraction of the material due to its increased length. (Section on SCP actuator fabrication under the appendix)

2. Bistability requires two SCP actuators to control. This duality is behind the oscillations that we are seeing. (Section on design of the bistable beam)

3. Due to this duality, symmetry is key. An ideal symmetrical situation would be the exact same amount of time to actuate during each cycle and the peak temperature of both actuators are consistent. (Section on results of the experiment)

2 Background

In order to understand how mechanical logic works, we first define what SCP actuator and bistable beam are.

SCP actuator The term actuator typically refers to a device that provides linear motion. Similar to a piston, a rod is pushed in the linear manner when voltage is applied. Unlike a motor, which is designed to spin from the shaft, an actuator is not intended for continuous shaft rotation, but for precise positioning. An actuator requires a control signal and a source of energy. The control signal is relatively low in energy and may be electric voltage or current. [1]

Because recently it has been discovered that by continually twisting polymer threads to an extreme until they form coils, an actuator is achieved with a power-per-weight, strain, and deformation rivaling or even exceeding that of human skeletal muscle. [2]

This type of twisted polymer is given a term, the supercoiled polymer actuator, abbreviated as the SCP actuator, we will refer to such twisted polymer as SCP actuator for the rest of the paper unless otherwise specified.

In order for SCP actuator to work with the rest of the mechanical logic, it needs to properly contract along the direction of the actuation force we drew in [Figure 1]. The contraction of the actuator begins with the heating up of the actuator via current from the power supply. The supercoils on the actuators attempts to expand in the presence of heat. However, the structure of the actuator, which is the shape of a spring, will force the supercoils to move in the lateral direction. Thus, the actuator will appear to have contracted.

Bistable Beam One of the well-known mechanical structures that have bistability is a beam or membrane that is buckled. When a clamped-clamped free standing structure is left with sufficiently large compressive stress, it buckles towards a direction parallel to the smallest dimension. [3]

There are many types of bistable beam. In this research, we are only concerned with two types of the bistable beam, the pre-compressed and pre-shaped bistable beam.

Pre-Compressed bistable beam: One way to create a buckled shape is to compress a beam from its ends using auxiliary actuators until it buckles. This method can precisely control a degree of buckling at any time. [4]

Pre-shaped bistable beam: A beam can be pre-shaped into a buckled fashion in a sinusoidal shape. This method can precisely control the level of buckling. One advantage of such mechanism is that the mechanically bistable mechanisms can apply a contact force without the need for continued actuation power.

3D structure The design and function of the 3D structure of mechanical logic can be found under Wenzhong?s research report. This work is not involved with the design of the mechanical logic. Instead we use the existing 3D design to accommodate for SCP actuator. The bistable beam is part of 3D design.

3 Design of Mechanical Logic

Design of SCP actuator In our research, we create actuators using a type of soft material, the nylon thread. The variety of nylon thread, its composition, and the production methods possess an important challenge in keeping the consistency of the material. In later sections, we will get into what exactly the challenge is, the procedures taken place to resolve this challenge, and the results produced that summarizes our work in choosing the appropriate material for our actuator.

The SCP actuator plays the role as the only actuator that can actuate, or push a mechanical switching device, in our case this switching device is a bistable beam. Given that our actuator is pushing on this switching device, we understand that the bistable beam is important enough that it deserves a section on its own. A rigorous presentation of the bistable beam is discussed in the following section.

Design of bistable beam We consider the use of pre-shaped bistable beam because pre-shaped bistable beam may allow one-sided actuation, thus eliminating the need for a two-sided actuation mechanism. One drawback of such one-sided actuation mechanism that turns us away from such advantage is that although a single actuation force can successfully Therefore, we adopt the pre-compressed bistable beam as our main venue as the mechanical switching device that provides bistability.

Because the bistable beam is securely clamped on both sides, this mechanical switch will have two states, as shown in [figure 1]. Arrow represents the actuation force from the SCP actuator.

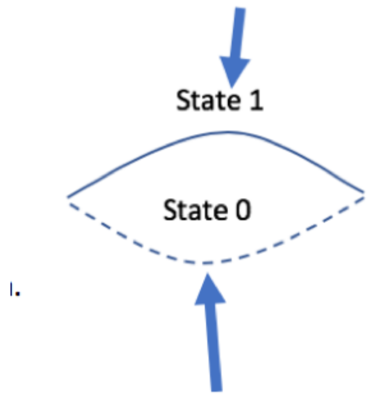

Figure 1: actuation force applying to the bistable beam. In state 1, an actuation force will be applied close to the midpoint of the beam, when the beam leave state 1, the actuation force will continue to apply to the beam as long as the actuator is still contracting from the heat. In state 0, the actuator that controls the beam in state 1 relaxes. The actuator in state 0 applies actuation force again to the beam so that the beam attempts to move to state 1. This process repeats again. And we argue that this process can repeat indefinitely as long as the bistable beam and SCP actuator are functional.

Clamped-clamped bistable beam Behind all the scenes of the actuation, the bistability is made possible by the boundary condition. Because the two end boundaries are securely attached to a platform, bistability is preserved.

4 Experiment and Results

Testing Mechanical logic and counting Oscillations First, we connect the SCP actuator to a constant current source in order to complete its circuitry [Figure 2].

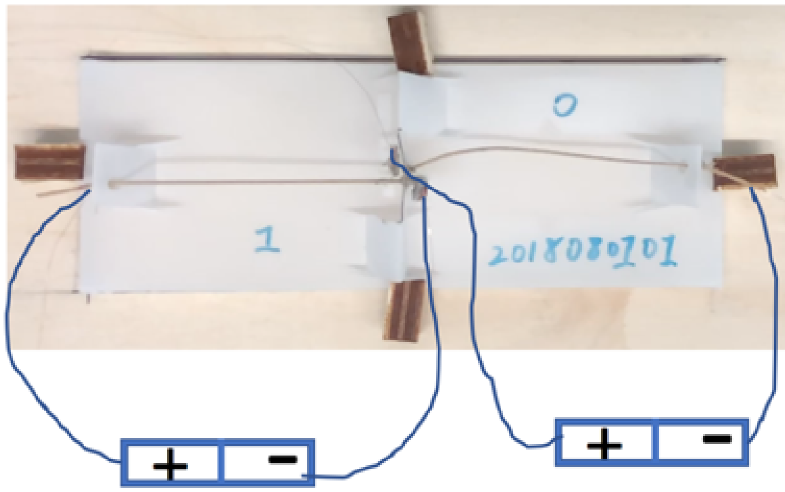

Figure 2: Mechanical logic and the completion of the circuitry through two constant current sources. The bistable beam of the middle either shuts off or turns on the circuitry depending on whether the SCP actuator is contracting or relaxing. A Contracting actuator indicates a closed circuit. A relaxing actuator indicates an open circuit. In this figure, the left circuit is closed while the right is open.

In order to determine the temperature and current changes in the actuator during the experiment, we use a thermo-camera and a constant current monitor [Figure 3].

We first apply a current to the left circuit in [Figure 2]. The SCP actuator heats up to about 40 degrees Celsius and contracts. The contraction actuates the bistable beam to the left, thereby cutting the connection of the actuator to the contact pad and opens the left circuit. But the right circuit connects because the right actuator is now long enough that it can reach the right contact pad, thus completing the right circuit. When a current run through the right circuit, the right actuator contracts until it pulls the bistable beam to the right and cuts the connection of the actuator to the contact pad. When the bistable beam has moved twice, one in each direction, it is said that the mechanical logic has oscillated once. We measure the number of oscillations by counting such movements.

Results of the experiment In our best result, we saw four complete oscillations. We summarize the current and temperature data of the experiment in [Figure 4] and [Figure 5], respectively.

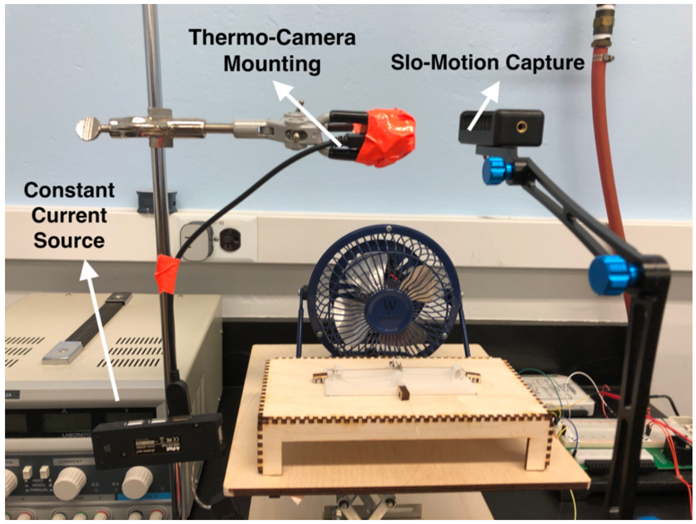

Figure 3: The setup for an experiment that records oscillations of mechanical logic. Thermo-camera records the temperature changes in SCP actuator. The Slo-Motion camera records the movement of bistable beam in slow motion. The Constant current source provides constant current to the mechanical logic. A fan in the middle cools down the mechanical logic in order to prevent the melting of bistable beam.

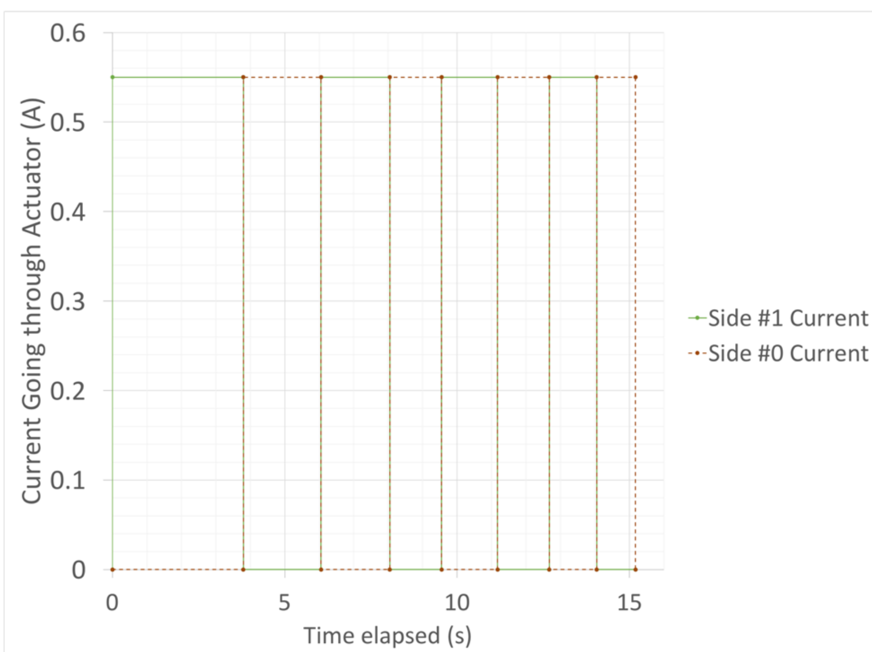

Figure 4: The current that ran through each actuator during the 4 oscillations. In the beginning of the experiment, current was required to raise the temperature from room temperature to the peak, so the first cycle takes a longer time to complete than the rest of the cycles. The average of the period of one oscillation is (3.8 ± 0.8) s. The error is the standard statistical error obtained from the standard deviation.

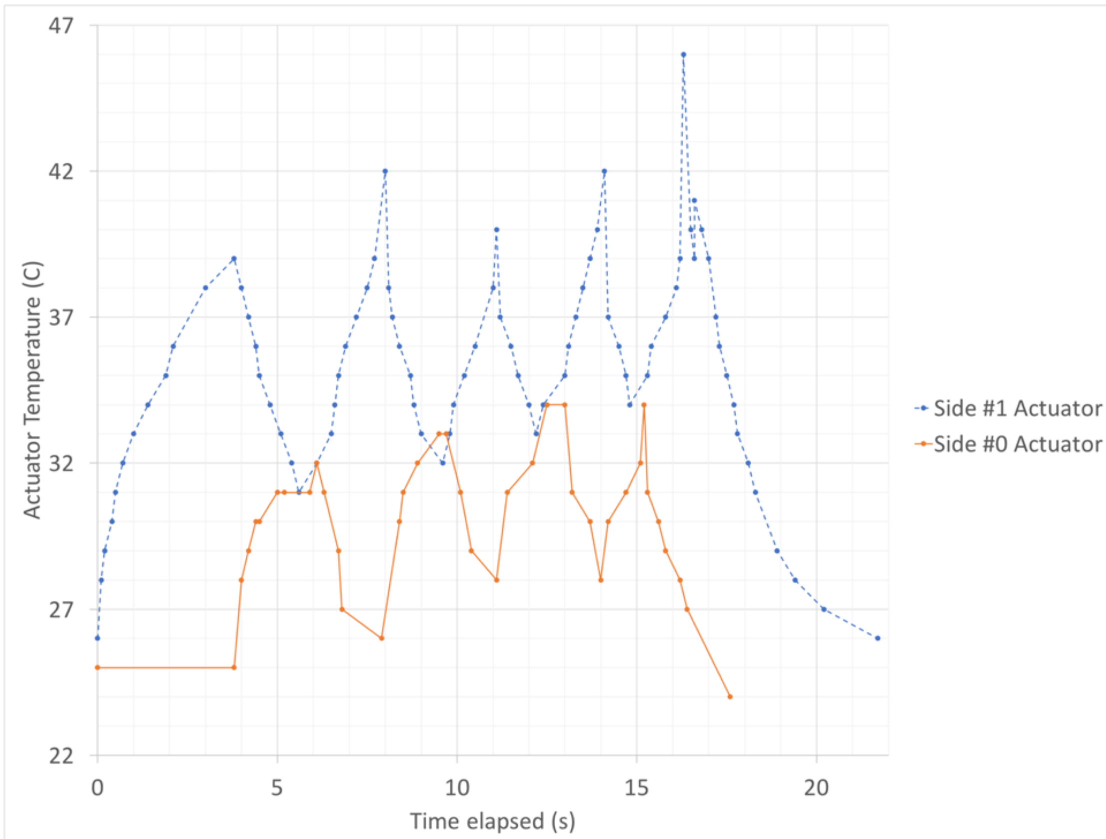

Figure 5: The temperature of the actuator as the mechanical logic oscillates. Each rise of the temperature indicates that the actuator is connected with the rest of the mechanical. Each fall of the temperature indicates an open circuit. There are four complete such rise and fall patterns in each of the actuators, which confirms that there were four complete oscillations on mechanical logic. The extra rise and fall of the temperature of side 1 shows that the actuator attempts to actuate the bistable beam, but the actuator fails to do so. Therefore, there is a high temperature rise of the actuator at when $t = 16.3$ s. This high temperature may have burnt the actuator and destroyed the connected from the actuator to the contact pad. A functional bistable beam after such loss of connection shows that the bistable beam did not contribute to the failure of another complete cycle. The difference in the peak temperature of the two actuator suggests asymmetry.

Note We synchronize the current with the temperature data by observing each start of the rise of temperature, which indicates a closed circuit. The temperature data taken from side 0 actuator is obtained manually by matching the color indicated on the spectrum of the thermo-camera with the color of the actuator. Since the thermo-camera was only able to detect the highest temperature, we can only estimate the temperature of the side 0 actuator.

5 Conclusion and Future Work

In the future, we hope to replace the constant current source to a battery so that our mechanical logic can perform without constraint of movement. In order to do so, we need to have a more stable means of connection from the contact pad to the actuator. Multiple complete oscillations suggest that our mechanical logic is able to oscillate indefinitely. This oscillation technique can be used by other scientists, researchers, or engineers to apply oscillation in the field of robotics with cost-effective materials.

6 APPENDIX: Notes on fabrication

6.1 Getting the right material for our SCP actuator

First, we worry about the source of our actuation force. In order to do so, we examine the annealing process for various types of threads. We can say that we found a proper SCP actuator when the actuator is able to contract for about 3mm without any tension.

In this work we look at three specific threads. We first use the thread we have been annealing since last quarter. In annealing, we used 0.45A current with 120, 160, and 200 g masses. These actuators are very stiff, have little or lateral spacing between the coils, have desirable strain under proper tension, and do not break during fabrication. Although this material is very strong, we worried about the small lateral spacing on the actuator.

We can attack this issue with a thread that is slightly less dense than our previous one. We order the thread from Technical Textiles (PN number: 20012123535HCB). In annealing, we used 0.45A current with 120, 160, and 200 g masses. These actuators are still very stiff, have little or o lateral spacing between the coils, desirable strain under stress, and occasionally breaks during fabrication. We are not satisfied with this material because it seems to stretch in the transverse direction instead of the lateral direction.

We move on to another thread from Technical Textiles (PN number 200121235343B). This thread is noticeably thinner and less dense than the previous ones. In order to reduce damage to the thread, we reduce the current applied to the thread. In annealing, we used 0.30, 0.33, 0.34, and 0.35A current with 50 g mass. This drastic reduction of mass is partially due to a 50% reduction in diameter of the thread. Even after the reduction of mass, the material is still subject to breakage. These actuators tend to have poor quality because they don?t have uniformly distributed coils, which causes contraction in undesired places and nonuniform heating when current is applied. Below is a figure of the three types of SCP actuators [Figure 6].

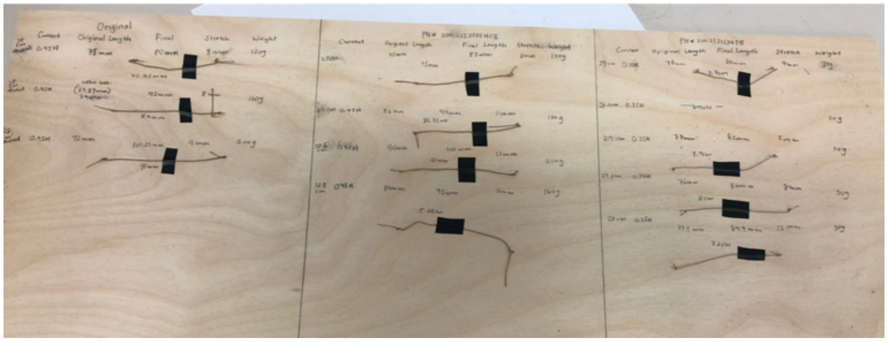

Figure 6: Three types of actuators made from different threads in an attempt to match thread to previous material. Left: Original kind (one used in previous quarter); Middle: PN number 20012123535HCB; Right: PN number 200121235343B

These three types of actuators are all considered undesirable because they do not contract laterally. We would like our actuators to contract laterally so that our thread will be able to apply the actuation force to the bistable beam in the correct direction and magnitude.

In order to obtain a larger strain, we apply a greater weight during annealing. When doing so, we abandon our last option of thread because it is too unstable for our experiment. We also abandon Our first source of actuator because its stiffness and density made the material seem less promising than our second option. We change the mass to 280 g. Current stays the same, 0.45A. We use 280 g of mass because it is the largest mass such that our actuator can withstand without too much damage to the actuator. We do not want to change the current because the amount of heating provided by the actuator does much more damage than the weight and provides little to no contribution to our desired output. With the increase in mass, we notice that the resultant actuator is much longer than the previous ones. This is promising to our goal of large strain of 3mm when current is applied without tension.

6.2 Testing SCP actuator on testing system

In order to verify the strain of SCP actuator, we use a bistable beam in a mock mechanical logic. We learned from last quarter that mechanical logic is very time consuming to build.

We first attach the SCP actuator onto the testing system. We then apply a current of about 0.45A. After many trials, we find that the SCP actuator contract more on its first oscillation than any of the later oscillations. Furthermore, we realize that the SCP actuator would contract on its own when left under room temperature, without tension. Usually when an actuator is 16 cm long, it would contract to about 12 cm in room temperature. This means that our actuators would contract for about 25% on its own! This means that when we are conducting an experiment, we will need to use the actuator within the day that it is created. If we don?t do this, our actuator might lose its strain.

6.3 Final Mechanical Logic and 4 complete Oscillations

In order to measure the oscillations of the bistable beam on the mechanical logic, we use the following procedures. To prep for the experiment, we first fabricate SCP actuators and mechanical logic. Since these two steps are generally unrelated, we can complete both tasks simultaneously.

SCP Actuator Fabrication We first fabricate the SCP actuators. We use the general procedures. First, we take a 35 cm long nylon thread of the model Technical Textiles (PN number: 20012123535HCB). Using a motor, we spin thread while it is under tension from 280 g of mass. Due to the spin and internal stress, the thread will automatically coil in the radial direction. The produced coils reduce the axial length of the thread. Typically, we produce a 10 cm long thread of coils from the 35 cm nylon thread.

While the 280 g of mass is still attached to the thread providing tension in the axial direction and after the thread is completely reduced into coils, we begin the annealing process, which will reduce the amount of stress in the coil and harden the material, thus making the actuator more spring-like. This annealing process is achieved by proper heating and cooling cycles. One complete cycle is defined as 15 seconds of heating by 0.45A of electric current and 15 seconds of room temperature cooling. One annealing process has 20 of such cycles. In order to maximize the strain of our actuator, we repeat this annealing process 5 times. As a result of constant tension from the mass, our SCP actuator will extend to about 20 cm. We noticed that the actuator will contract under room temperature if we remove tension, so we will only use the actuators fabricated in the same day of our experiment.

Mechanical Logic Fabrication Next, we fabricate mechanical logic. In order to do so, we first print our design from a paper cutter [Figure 7].

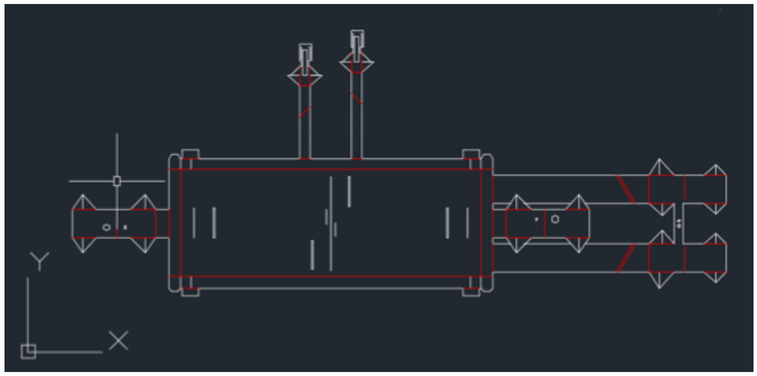

Figure 7: design of our mechanical logic in 2D format in CAD. The red lines in the design will be scored during cutting. The white lines indicate a regular cut. We check each mechanical logic after fabrication in order to ensure symmetry and flawless bistable beam and contact pad. Picture is reproduced by permission of the designer Wenzhong Yan.

We then fold the printed 2D sheet along the scored lines. The bistable beam is folded first followed by the support structure and finally the mechanical contact pads [Figure 8].

Figure 8: Two fabricated mechanical logic. When fabricating, the key is to check for the bistability of the beam along every step of the beam. We make sure that the bistable beam is not folded or damaged in any way. Any change to the bistable beam that reduces its bistability will result in a complete redo of the fabrication process.

Finally, we assemble the SCP actuator along with our mechanical logic [Figure 9].

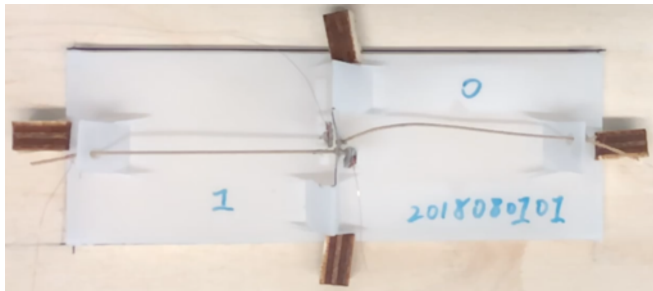

Figure 9: The final assembly of mechanical logic along with one SCP actuator. A 15 cm long actuator is cut into two equal sizes. These two pieces are then assembled onto the mechanical logic via thin threads. Contact pads are covered with aluminum foil.

References

[1] "Actuator". www.en.wikipedia.org. Archived from the original on 2018-07-31. Retrieved 2018-08-16.

[2] Yip, Michael C., and Gnter Niemeyer. "High-performance robotic muscles from conductive nylon sewing thread." *Robotics and Automation (ICRA), 2015 IEEE International Conference on.* IEEE, 2015.

[3] Qiu, Jin, Jeffrey H. Lang, and Alexander H. Slocum. "A curved-beam bistable mechanism." *Journal of microelectromechanical systems* 13.2 (2004): 137-146.

[4] Cazottes, Paul, et al. "Bistable buckled beam: modeling of actuating force and experimental validations." *Journal of Mechanical Design* 131.10 (2009): 101001.

[5] Cho, Kyeong Ho, et al. "A robotic finger driven by twisted and coiled polymer actuator." Electroactive Polymer Actuators and Devices (EAPAD) 2016. Vol. 9798. International Society for Optics and Photonics, 2016.

[6] Arakawa, Takeshi, et al. "Position control of fishing line artificial muscles (coiled polymer actuators) from nylon thread." Electroactive Polymer Actuators and Devices (EAPAD) 2016. Vol. 9798. International Society for Optics and Photonics, 2016.

[7] Haines, Carter S., et al. "New twist on artificial muscles." Proceedings of the National Academy of Sciences 113.42 (2016): 11709-11716.

[8] Carrico, James D., Kwang J. Kim, and Kam K. Leang. "3D-printed ionic polymer-metal composite soft crawling robot." Robotics and Automation (ICRA), 2017 IEEE International Conference on. IEEE, 2017.

[9] Simeonov, Anthony, et al. "Bundled Super-Coiled Polymer Artificial Muscles: Design, Characterization, and Modeling." IEEE Robotics and Automation Letters 3.3 (2018): 1671-1678.

[10] Zhang, Jun, et al. "Modeling and Inverse Compensation of Hysteresis in Supercoiled Polymer Artificial Muscles." IEEE Robotics and Automation Letters 2.2 (2017): 773-780.