Worcester Polytechnic Institute
Major Qualifying Project

Light Actuated Microvalve

A Major Qualifying Report Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

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Degree of Bachelor of Science.

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Abstract

The objective of this project was the design and fabrication of a microvalve powered by light driven actuators (LDA) manufactured from single-walled carbon nanotubes (CNTs) polydimethylsiloxane solution. Our team executed two different methods of CNT-actuator fabrication to determine which process yielded optimal elastic deformation behavior for valve application. The final CNT-polydimethylsiloxane elastomer solution underwent a series of designed experiments to observe the LDAs mechanical behavior in reaction to photons. Our team collected quantitative lab data to analyze its mechanical properties and calculate the force applied due to its deformation. Computer aided design (CAD) was utilized to conceptualize a preliminary LDA microvalve prototype. The motivation behind this project was to conduct research on potential LDA applications as propulsion components in future light driven microelectromechanical systems.

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Chapter 1: Introduction

1.1 Motivations

In this section, our team addressed the motivating real-world applications for the work conducted throughout the duration of the report. We examined various areas of application including how to advance general actuation and the aerospace and energy industries. The purpose for the research and testing conducted on light driven actuation technology is to uncover its potential capabilities in future light driven microelectromechanical systems.

1.1.1 General Actuation

Actuation consists of the process of converting an energy source into mechanical motion. This is achieved through the utilization of devices known as actuators. Actuators are components of a device or machine that work to achieve physical movements through the conversion of an energy source. The typical energy sources used by actuators are electrical, pneumatic, or hydraulic. Actuators are critical to any machine as they enable movement. Two types of actuators are linear and rotary. Linear actuators create motion in a straight line and are utilized in machines such as printers, sprayers, computers, and valves. Rotary actuators enable circular motion and are utilized in applications like conveying, clamping, transferring parts, positioning, and valve control.

Due to accessibility, our project used DC powered electrical actuators as inspiration. Electrical linear actuators consist of a DC input voltage that runs to a stator and rotor. The current flowing through the copper coils of the stator generates a magnetic field which causes the rotor to rotate. Essentially this acts as a motor which drives a motor shaft, which rotates linearly back and forth among the system's limits. The gears are used to control the speed and force of the actuator. A general guideline is that a lower gear ratio leads to lower force but higher speeds. The limit switches are used as control signals to direct motor direction. Without limit switches, the actuator would drive indefinitely in one direction leading to eventual DC motor failure. (Team, 2018).

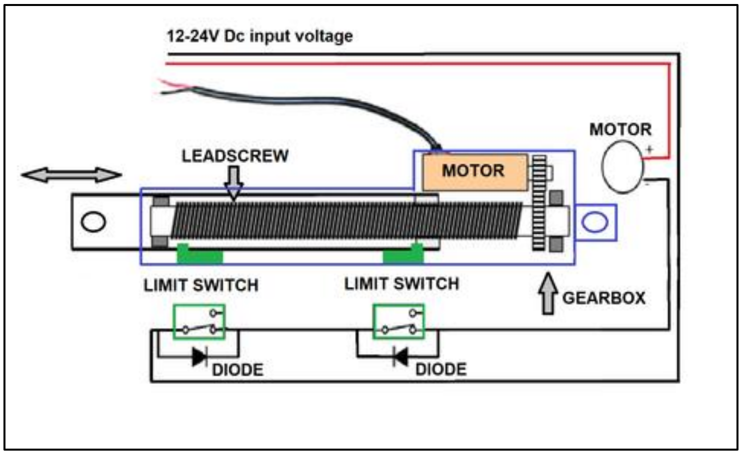


Figure 1: DC Electrical Linear Actuator Schematic

1.1.2 Traditional Propulsion Systems

Actuation is a key component in the control of propulsion systems seen in the aviation industry. Propulsion systems are machines that produce thrust to push an object forward. Thrust is a mechanical force whose generation is dependent on the mass flow through an engine and the exit velocity of the gas (Hall, 2021). The mass flow through the engine is controlled through a variety of mechanisms including actuated valves. For airplanes, thrust is typically generated through some application of Newton's third law of action and reaction. A working fluid is accelerated by the engine and the reaction of this produces a force on the engine. Due to the intense conditions that accompany aviation, the engine and its components must have the ability to operate effectively. The most important requirements on the motors include optimal volume/performance ratio, low power consumption, temperature resistance, long life, resistance against vibrations and impact, and high corrosion resistance. Actuators used in these applications need to be light weight, small enough to fit in confined spaces, and possess the ability to withstand ambient conditions mentioned above (maxon, 2021).

1.1.3 Electric Propulsion Systems

Electric propulsion is becoming a heavily researched area in space propulsion systems. A major advantage of this substitution is the reduction of the required propellant mass compared to traditional chemical rockets. This transition has the potential to greatly decrease the overall launch mass of a spacecraft. These systems utilize electrostatically charged and accelerated nanoparticles as a propellant. The intended purpose is to provide altitude control and acceleration. The functionality of electric propulsion is as follows: "Conductive nanoparticles would be transported to a small liquid-filled reservoir by a micro-fluidic flow transport system. Particles that come into contact with the bottom conducting plate would become charged and pulled to the liquid surface by the imposed electric field. If the electrostatic force near the surface can cause charged nanoparticles to break through the surface tension, field focusing would quickly accelerate the particles through the surface. Once extracted, the charged nanoparticles would be accelerated by the vacuum electric field and ejected, thus generating thrust." (Berger, 2007)

1.1.4 Fuel & Energy Actuation

Utility power generation involves complex power systems using hundreds of valves to control nearly every aspect of operation. The valves are controlled via an actuator and are used for applications like pollution control, feed water, cooling water, chemical treatment, and steam turbine control systems. The actuators are responsible for regulation mass and energy flows by adjusting valve position. In combination, the actuator and valve create a single unit – the control valve. They play a critical role in the optimization of plant efficiency and are the final control element in the operation of a power plant. Due to the harsh environments, they are exposed to, control valves must possess the ability to withstand exposure to a variety of chemicals, abrasive materials, and high temperatures. The current state of innovation for these styles of valves focuses on the withstanding the demanding environments they are exposed to. Traditionally, control valves are powered by pneumatic, hydraulic, or electrical energy (Ray, 2015).

1.2 Objectives of Major Qualifying Project

The overarching goal of this project is to design and fabricate a microvalve powered by light driven actuators (LDA) manufactured from a single-walled carbon nanotube (CNT) polydimethylsiloxane solution. To achieve this goal, the following three subsequent objectives must first be met: (1) execute a refined fabrication process to develop microfilms of light reactive actuators from a CNT-Polydimethylsiloxane (PDMS) solution, (2) test and analyze the mechanical properties of the light driven actuator assemblies in response to light and (3) design and model a light actuated microvalve prototype. Our team executed two different methods of CNT-actuator fabrication to determine which process yields optimal elastic deformation behavior for valve application. The final CNT-polydimethylsiloxane elastomer solution will undergo a series of designed experiments to observe the LDAs mechanical behavior in reaction to photons. Our team can then proceed to collect quantitative lab data to analyze its mechanical properties and calculate the force applied due to its deformation. Computer aided design (CAD) will be utilized to create a preliminary LDA microvalve prototype specifications.

1.3 Paper Outline

This report will begin by covering background information required to better understand LDA's and further explain the use of microelectromechanical systems, the basis of light driven actuation, and the materials often associated with each technology. It will then proceed to describe the different methodologies used in developing the CNT- polydimethylsiloxane solution and the mechanical testing of the final fabricated LDA. Finally, our team will present our qualitative and quantitative findings, resulting conclusions made, and future recommendations for further research.

Chapter 2

Background: Materials and Piezoelectric Actuation

2.1 Nanotechnology

2.1.1 Description

Nanotechnology is defined by the National Nanotechnology Initiative as the manipulation of matter with at least one dimension sized from 1 to 100 nanometers (National Nanotechnology Initiative, n.d.) To put this in perspective a sheet of newspaper is about 100,000 nanometers thick. (National Nanotechnology Initiative, n.d.). The use of nanotechnology allows individual atoms to be manipulated at this level leading to changes in physical and chemical properties of the material creating what is known as a nanomaterial. The beginning of the modern nanotechnology movement began in 1981 when the scanning tunnelling microscope was developed which allowed scientists to see individual atoms (National Nanotechnology Initiative, n.d.). This breakthrough in microscopic technology then allowed the opportunity to manipulate atoms to build different structures and create nanomaterials.

2.1.2 Current & Theoretical Applications

Many mechanical, chemical, and optical properties can change at the nano-particle level which exemplifies the advantages of nanotechnology. These unique properties are the main reason why nanotechnology is on the rise in breakthrough technology in a variety of scientific industries. Some of these industries include medicine, energy, automotive, textiles, electronics, and more. The reason that it can be utilized broadly across many industries with wildly different functions is because nanotech is not confined to one material with a set of specific properties. There is an array of nanomaterials that hold properties that are useful in each of the industries mentioned above. Nanotechnology can be categorized into two subsections: bottom-up and top-down approaches. The bottom-up approach “use(s) chemical or physical forces operating at the nanoscale to assemble basic units into larger structures” (Picraux, 2005). This method begins with arranging the smallest particles in the system to create larger systems providing the desired functions. A simple example of this method is a chemical reaction that takes two atoms to create a more complex compound. The top-down approach strives to build structures at the microscale in order to then manipulate atoms at the nanoscale (Picraux, 2005).

2.2 Microelectromechanical Systems

Microelectromechanical Systems (MEMS) are generalized as "technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication" (MNX, 2022). The typical dimensions of MEMS can range from less than 1 micron to several millimeters. The primary criterion of MEMS is the presence of elements with some sort of mechanical functionality. Some of the functional elements standardly utilized in MEMS include miniaturized actuators, sensors, electronics, etc. A major benefit of MEMS is the relatively low cost of manufacturing without trading off reliability. Fabrication of MEMS consists of the utilization of tools and materials employed in integrated-circuit (IC) manufacturing. MEMS require no additional assembly. The development of MEMS dates to the 1980s with the development of an automobile air bag controller (Picraux, 2016). Emerging products utilizing MEMS include semiconductor chips for radio frequency applications, biochemical sensors, microvalves (for fuel and gas flow), optical switches, microresonators, micropumps, and microflaps (to modulate airstreams).

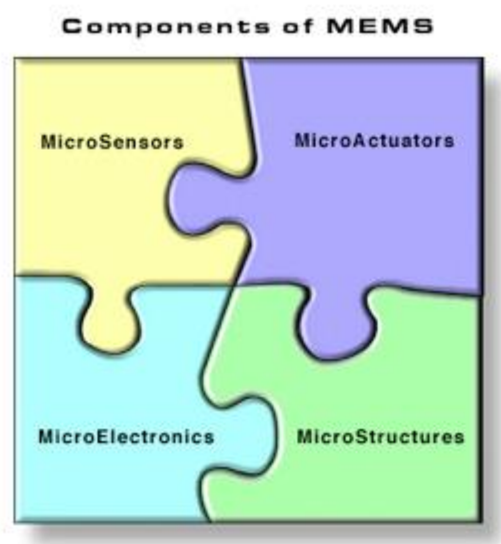


Figure X: Components of MEMS

2.3 Light Driven Actuation

2.3.1 Description

In the simplest of terms, light actuation is the process of converting photonic energy into mechanical motion. The essence of light driven actuation is the choice of appropriate photothermal material that converts the light energy into heat energy to induce a mechanical deformation (Ramakrishna, Singh, Tiwari, 2021). Common photothermal materials used to carry out this conversion of energy include nanotubes, polymers, or crystal-polymer hybrids. Means of testing light-actuated materials are paired with different light distribution mechanisms like lasers, flood lights, and micro-LED's. Light-driven actuation of synthetic polymers is an emerging field of interest because it offers simple remote addressing without complicated hydraulic, electric, or magnetic systems (Bhatti, 2022) with the hope of one day replacing the need for traditional means of mechanical actuation from electrical wiring and micromotors.

2.3.2 Former WPI Projects

Two previous WPI research projects related to light driven actuation have been conducted during the years of 2018 and 2021. The 2018 study titled "*Light Driven Actuators*" examines the basics of using light as clean energy to power mechanical systems. Similar to the CNT-PDMS solution, the technical work executed in this report combines graphene nanoplatelets (GNPs) with polydimethylsiloxane (PDMS) into a polymer to study its thermal conductivity and photomechanical actuation. The goal of this project was to determine which wt% of GNPs to PDMS would yield a solution with the best photomechanical properties.

The 2021 study titled "Optically Driven Robots" examines the use of CNTs ability to replace traditional robotic systems. The team aimed to refine a CNT-elastomer LDA manufacturing process, ultimately developing a robotic inchworm utilizing a CNT actuator as the body with rigidly attached 45-degree angle feet. Mechanical testing of the robotic inchworm was conducted to record its general displacement and velocity capabilities. Access to both reports can be found in Appendix 1.

2.4 Piezoelectric Materials

Piezoelectric refers to the phenomenon of a material producing an electrical charge under the application of a mechanical stress (compression, torsion, bending, etc). Some common piezoelectric materials include bone, crystals, specific ceramics, DNA, enamel, and silk. Piezoelectric materials also can experience the phenomenon known as the "Inverse Piezoelectric Effect", in which a material produces an internal generation of mechanical strain in response to an applied electrical field. Piezoelectricity is represented by the following equation:

$$P = d \times \text{stress}$$

where d is the piezoelectric coefficient of a given material. Piezoelectric materials are utilized in various industries such as manufacturing, medical devices, telecommunications, automotive, and information technology. Specific technological applications of piezoelectric materials include actuators, high voltage power sources, and sensors (Tiwari, 2020).

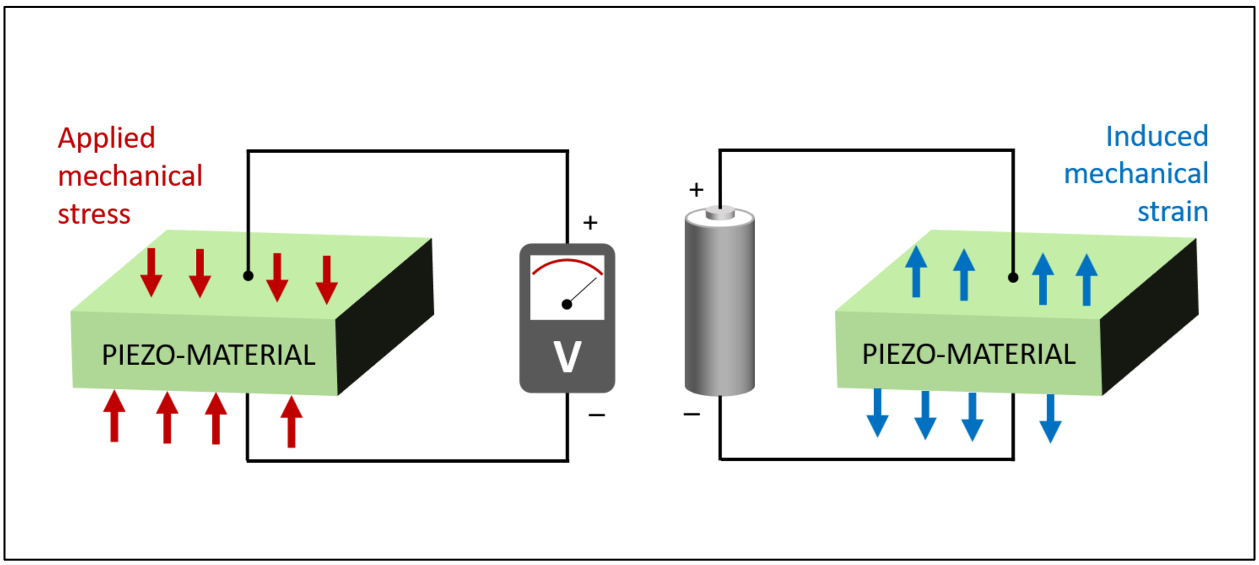


Figure 3: Schematic of Piezoelectric and Inverse Piezoelectric Effect

CNTs are piezoelectric materials that have demonstrated the ability to exhibit abnormal flexoelectric properties. The total internal electrical field of a CNT is zero due to its cylindrical symmetry but breaking this symmetry has been shown to lead to significant electric polarization. "The above studies allowed us to conclude that a non-uniform strain of CNTs and, consequently, the violation of its cylindrical symmetry will lead to the appearance of flexoelectric and/or surface piezoelectric effects and the appearance of an internal electric field in the nanotubes" (Il'ina, 2018, p. 18-19). This ability was a relevant consideration to our project due to the functionality of our valve (see Chapter 4).

2.5 Standard Valve Designs

A valve is a component that is used to control and direct flow through a system. The function of valves across any system includes the stopping and starting of flow, controlling the pressure of flow, controlling the direction of flow, and many other specific functions (Unified Alloys, 2022). The mechanical motion of controlling a valve can be placed into three categories: Manual valves, actuated valves, and automatic valves. A manual valve is a valve that is controlled by hand such as a garden hose that most commonly uses a hand wheel to actuate a gate or a globe valve (2). An actuated valve is controlled by an actuator system such as a hydraulic or pneumatic system. These can be seen in large scale or high precision flow systems (Unified Alloys, 2022). An automatic valve is controlled by actuators that can be set to regulate flow when a certain parameter is reached such as pressure or temperature. The factors that need to be considered when choosing or designing a valve all depend on the application it is being used for. Some of these factors include media type, application conditions, valve function, actuation method, and maintenance requirements (Hensler, 2019).

Chapter 3

Methodology: Carbon Nanotube Film Fabrication

3.1 Methodology & Materials

3.1.1 Material Selection

The production of the LDAs consisted of two materials: Single-Walled Carbon Nanotubes (SWCNTs) and Polydimethylsiloxane (PDMS). The combination of the SWCNTs and the PDMS created a nanocomposite that was able to be manipulated to be used as an actuator in the microvalve design.

SWCNTs are a nanomaterial derived from sheets of graphene being rolled up into tube-like structures. They are “one-dimensional objects” due to the wall thickness of the hollow cylinders to be one atom thick (Cheap Tubes, n.d.). The importance of the development of SWCNTs is due to the unique mechanical and optical properties that they exhibit. SWCNTs have calculated values of tensile strength that are approximately 100 times greater than that of steel (Jansen et al., n.d.) and an elastic modulus of SWCNTs that is approximately 5 times greater than steel (Kang et al., 2020). They show great material properties that can be utilized in a number of applications in future research. SWCNTs also possess interesting optical responses to photons. When light passes through a SWCNT an electric field inside the tubes can be created that in some cases are twice the value of the light waves (NPG Asia Materials, 2009). This electric field will create a mechanical deformation of the nanocomposite due to the piezoelectric characteristic of the SWCNTs.

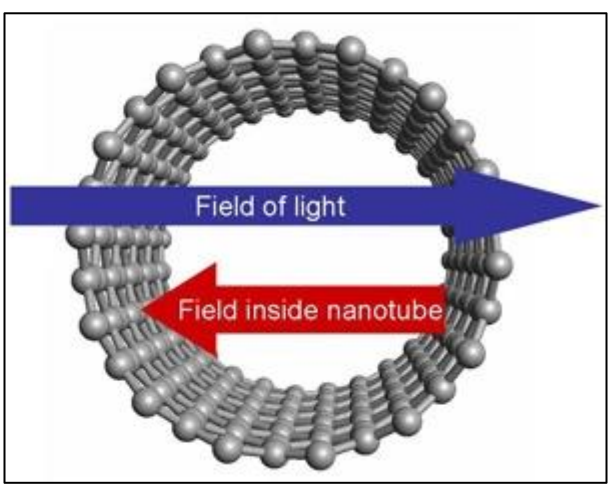


Figure 4: Optical response of SWCNTs (NPG Asia Materials, 2009)

The use of Multiwalled Carbon Nanotubes (MWCNTs) was also considered for this application which consists of multiple layers of graphene sheets being rolled up to create concentric single-walled tubes. The reason for opting with the SWCNTs was due to their more favorable mechanical properties in tensile strength and elastic modulus. SWCNTs have an elastic modulus of about three times greater and a tensile strength of about two times greater than MWCNTs (Filchakova & Saik, 2021)

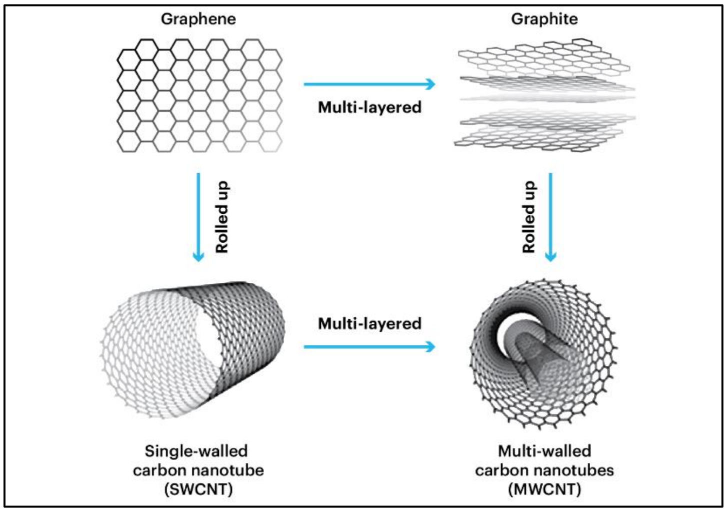


Figure 5: Depiction of difference between SWCNTs and MWCNTs

(Filchakova & Saik, 2021)

The most developed process of producing SWCNTs is known as Chemical Vapor Deposition (CVD). The CVD process produces a good yield of high purity SWCNTs and is easily scalable which is why it leads the commercial production industry. The key steps of the CVD production process can be seen below in figure 6. The leading manufacturer of SWCNTs is OCSiAl who produce tens of tons of SWCNTs annually (Filchakova & Saik, 2021).

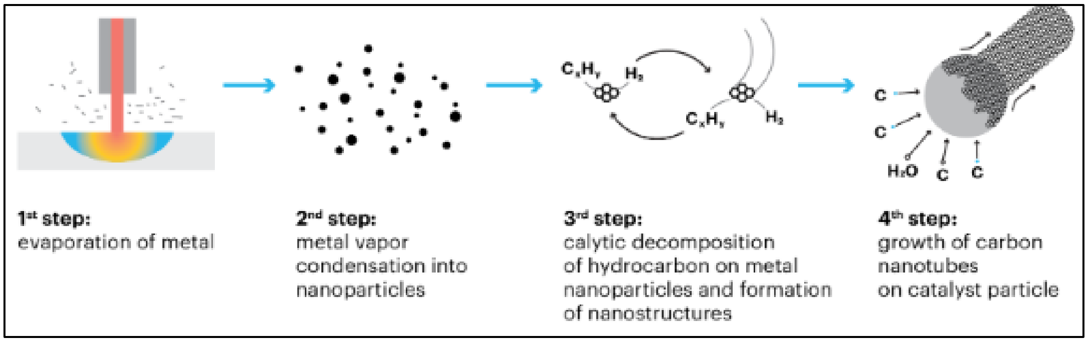


Figure 6: Key Steps in the standard CVD production process (Filchakova & Saik, 2021)

Polydimethylsiloxane (PDMS) is a silicon-based polymer that is used to house the SWCNTs and form the shape of the LDAs. PDMS is the most widely used silicon-based organic polymer and has many practical applications ranging from contact lenses to elastomers and lubricating oils (ChemEurope, n.d.). PDMS is a viscoelastic material which means that it has characteristics similar to both liquids and solids. Due to its molecular arrangement PDMS can be manipulated in different ways that will best fit its application. To create the LDAs, liquid-like properties were used to disperse the SWCNTs throughout the PDMS to create a homogenous mixture. Then the solid-like properties were used by adding a crosslinker to shape and solidify the PDMS.

3.1.2 Process 1

Process 1 began by mixing 85mL of deionized (DI) water and 15mL of 70% isopropyl alcohol (IPA) into a beaker. Based on the desired concentration, the CNTs were measured out and added to the DI-IPA solution. Example ratio of CNT-solution is 1mg/100mL. Next, the solution was placed in a sonicator for 2 hour on/off intervals for a 20-hour total period (2 hours on, 2 hours off). A time sheet was utilized to track progress and ensure the sonicator did not reach over 35° Celsius. Once the solution was ready, it rested for 20 minutes.

In a chemically safe environment (preferably a clean room wearing protective gear) a filter holder and disk apparatus was prepared over a beaker. The funnel was mounted, and the desired filter membrane was selected to be placed in the center of the apparatus to begin vacuum filtration. After the vacuum filtration device was prepared and turned on, 100mL of DI water was added to soak the membrane and then proceed to pour the 100mL CNT-solution. The solution droplets completely passed through the filter to ensure that no solution was wasted. 25mL of IPA was added to wash the previous SDS and add another 300mL of DI water until no droplets remain, again ensuring that the solution had completely passed through the filter. Once completed, the vacuum filtration was turned off, the funnel was disassembled, and the remaining CNT membrane was removed. The membrane was secured to a circular petri dish using clear single-sided elastomer (clear single sided scotch tape) and left to sit for 10 minutes. A layer of double-sided elastomer and a layer of PVC film were added on top of the membrane, as shown in figure 7. Finally, the elastomer-CNT membrane was peeled off the filter secured to the petri dish and cut into desired actuator sizes.

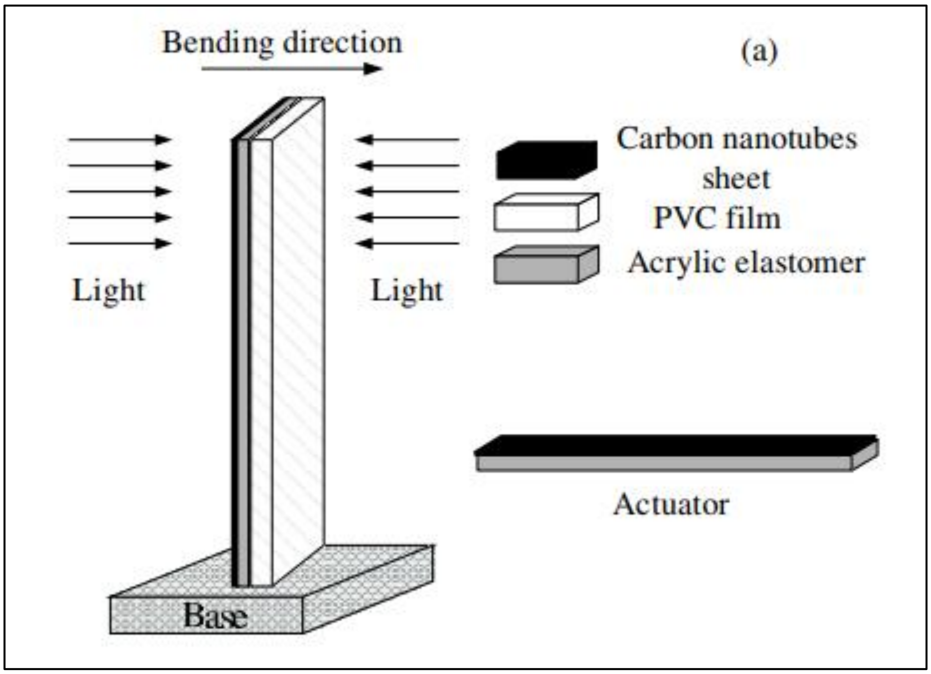


Figure 7: Diagram of Process 1 CNT film actuator *(Lu, Panchapakesan, 2005)*

3.1.3 Process 2

Process 2 consisted of a different fabrication method than process 1. The solution developed contained CNTs being dispersed into polydimethylsiloxane (PDMS) at a standardized weight percentage of 1% CNTs. The following equations represent the wt % calculations of the solution:

$$\boldsymbol{wt\% = \frac{weight\ of\ CNTs}{weight\ of\ PDMS}}$$

$$\boldsymbol{Mass\ of\ CNTs = (Mass\ of\ PDMS) * (0.01)}$$

$$\boldsymbol{Solution\ Mass = (Mass\ of\ PDMS) + (Mass\ of\ CNTs)}$$

Approximately 25 grams of PDMS Sylgard 184 elastomer were measured out. The CNTs were weighed and added to the PDMS based on the intended wt% calculated above. The solution was then shear mixed in 2-hour intervals, for a total of 10 hours, to fully incorporate the CNTs into the PDMS and create a homogeneous solution. The cross-linking agent, hydrosiloxane, was added at a weight ratio of 1:10 and shear mixed for 5 minutes. The solution was placed in a degasser for 30 minutes to remove any air bubbles. After, the solution was poured on 1.2 mm glass microscope slides and spin coated at 750 rpm for 150 seconds. Finally, the slides were baked at 125℃ for 20 minutes. This process successfully produced a 0.4mm thick light reactive elastomer.

3.2 Results & Discussion

3.2.1 CNT Actuator 1

Process 1 yielded less than optimal results. Although our team was able to successfully manufacture the CNT film actuator, it was unable to fulfil all three project objectives. The final fabrication was cut into 10mm by 20mm strips and taped down to the lab bench as seen in figure (X). The actuator did bend when under light, however the level of displacement and its weak structure would not be sufficient or applicable for the microvalve design. Process 1 was also a long and tedious manufacturing process requiring over a 24-hour period to manufacture one membrane.

Figure 8: Process 1 CNT film actuator testing

3.2.2 CNT Actuator 2

Process 2 produced a solution capable of fulfilling our project objectives and was therefore chosen as the method to fabricate actuators. The elastomer was cut into 7- 9mm long strips for mechanical testing. The elastomer strips were layered in different increments to observe the response discrepancies to light. The table below shows the dimensions of the testing samples:

Table A: Dimensions of CNT actuators

No. of Layers	**1**	**3**	**4**	**10**
Thickness (mm)	0.4	2.2	4.6	6.9
Width (mm)	8.2	8.3	9.0	7.5

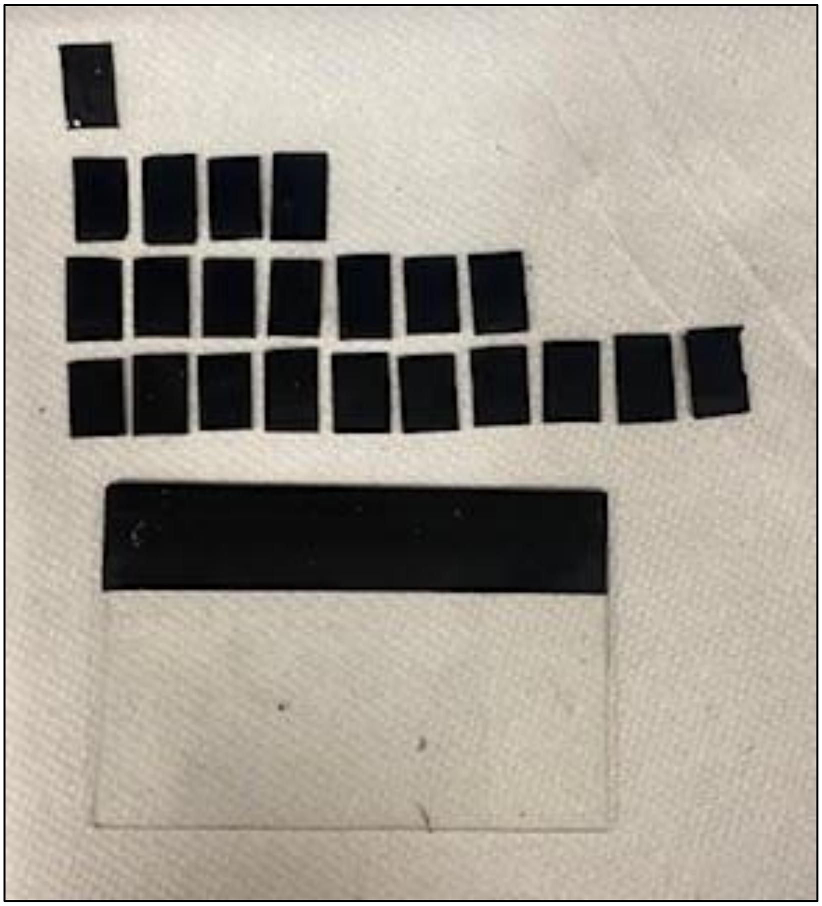


Figure 9: Process 2 CNT actuator test strips

The experimentation process consisted of fastening the actuator assembly samples vertically between two clamps in a previously designed dynamometer. The photomechanical actuation response of the elastomer strips was measured in intervals of 3 minutes for a total of 6 cycles. The light source was a 400-Watt incandescent light bulb. The scale data produced by the dynamometer was video recorded and analyzed in 10 second increments. The photomechanical effects demonstrated by the actuators included thermal expansion and the inverse piezoelectric effect.

3.3 Modeling & Analysis

3.3.1 Stress Analysis

The photon stimulus from the light source produced a subsequent deformation in the LDAs. The immediate stress on the LDAs was calculated from the changes in mass due to its mechanical deformation. The changes in mass were converted to represent the instantaneous force applied.

$$\boldsymbol{\sigma = \frac{F}{A} = \frac{m * 9.81}{d * w}}$$

σ = Stress [Pa], *F = Force [$\frac{kg*m}{s2}$], A = Area[mm^2], m = Mass [kg],*

d = thickness [mm], w = width [mm]

The strain, $\boldsymbol{\epsilon}$, was calculated from the applied stress and the elastic modulus of PDMS (615 kPa).

$$\boldsymbol{\epsilon = \frac{\sigma}{E}}$$

The maximum stress and strain exhibited by each actuator is shown in the table below.

Table B: Stress and strain by actuator layer

No. of Layers	Thickness (mm)	Max Stress (kPa)	Maximum Strain
1	0.4	0.288916	0.47E-3
4	2.2	18.47557	30.042E-3
7	4.6	7.422	12.06829E-3
10	6.9	5.523048	8.981E-3

The test data was recorded in a Microsoft Excel spreadsheet which was used to calculate and plot the stress response of the actuator sample against the time.

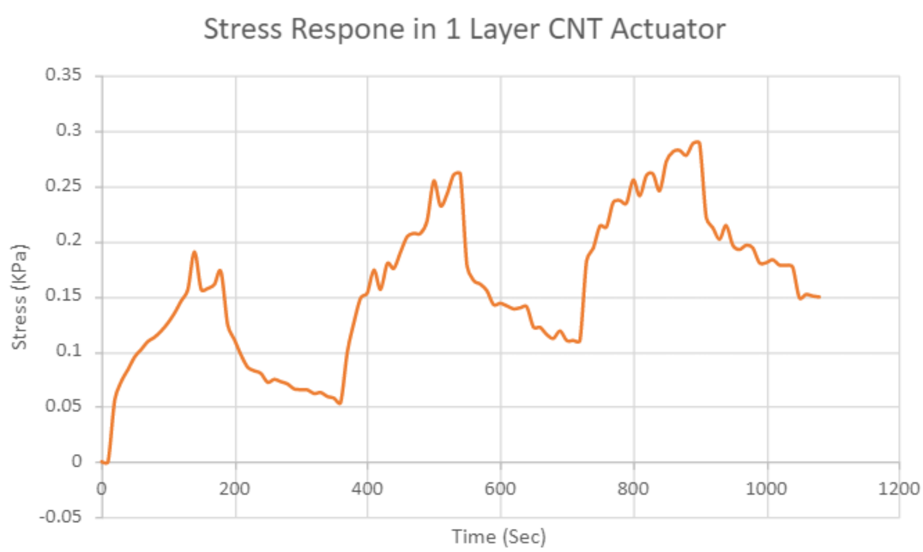


Figure 10: 1 Layer CNT actuator stress plot

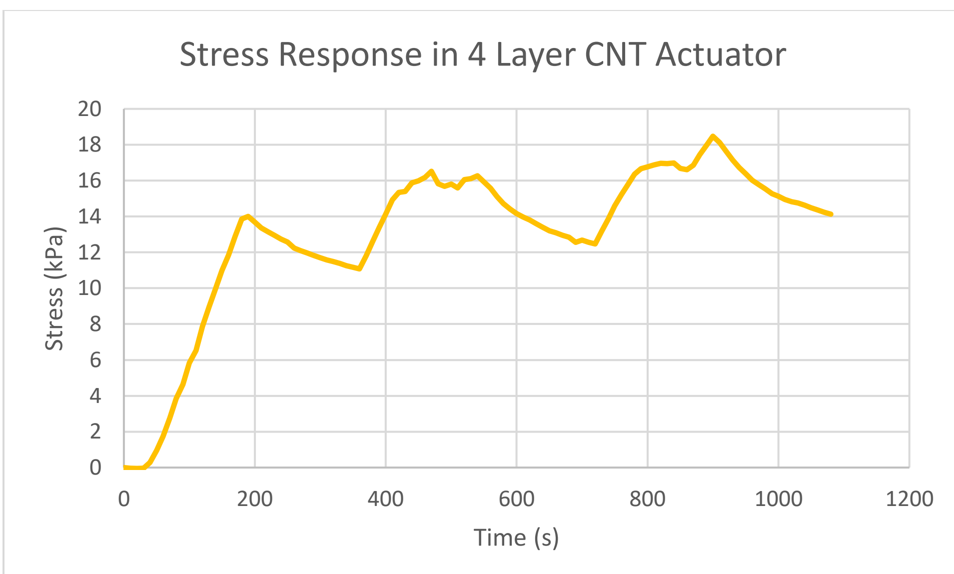


Figure 11: 4 Layer CNT actuator stress plot

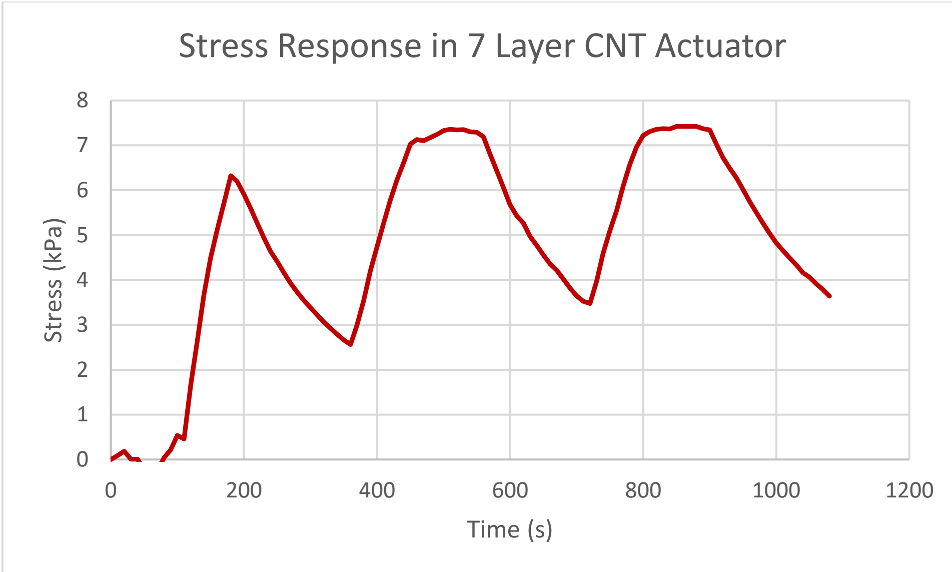


Figure 12: 7 Layer CNT actuator stress plot

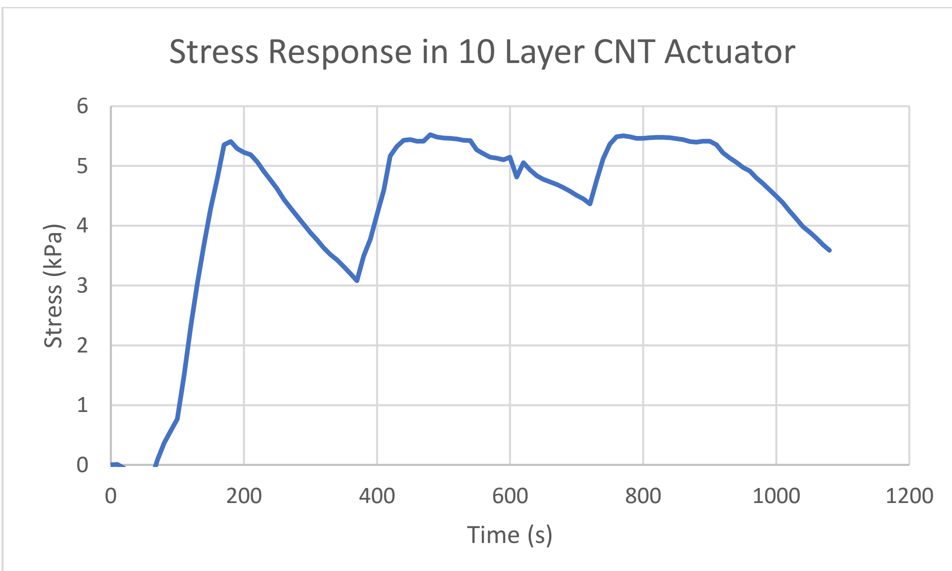


Figure 13: 10 Layer CNT actuator stress plot

The 10 Layer CNT Actuator demonstrated abnormal expansion and contraction behavior leading our team to conclude that the actuator experienced damage either during handling or due to thermal fatigue. The thermal fatigue was likely due to the continuous operation of the incandescent light source. For this reason, the 10-layer actuator was excluded from the complete stress comparison plot shown below.

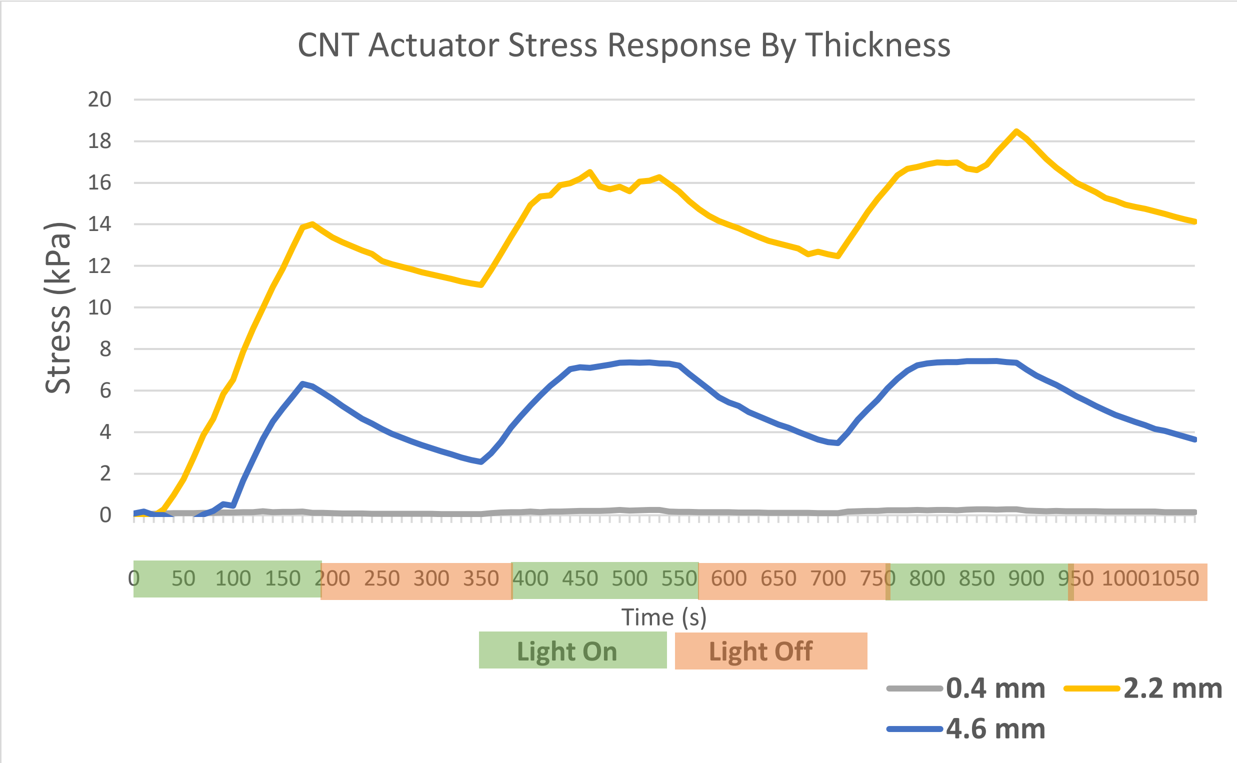


Figure 14: Stress plot comparison of all CNT actuators

3.3.2 Piezoelectric Analysis

While our project team did not focus on the piezoelectric elements of the CNT actuators developed, the theoretical piezoelectricity discharged by the actuators was analyzed. The photons from the light source react with the graphene in the CNTs to produce a mechanical stress. The mechanical stress initiates the inverse piezoelectric effect in the CNTs causing a piezoelectric charge. As discussed above in section 2.4, the piezoelectric output of a material is defined as the product of the stress and the piezoelectric constant of a given material. The piezoelectric constant of CNTs is approximately 0.107 C/m^2. The theoretical piezoelectric output of each actuator based on maximum stress is shown below.

Table C: Theoretical piezoelectric output of CNT actuators

No. of Layers	1	4	7	10
Max Piezoelectric Output [C*kPa/m^2]	0.030914	1.976886	0.794154	0.590966

Chapter 4

Light Actuated Valve

4.1 Valve Design

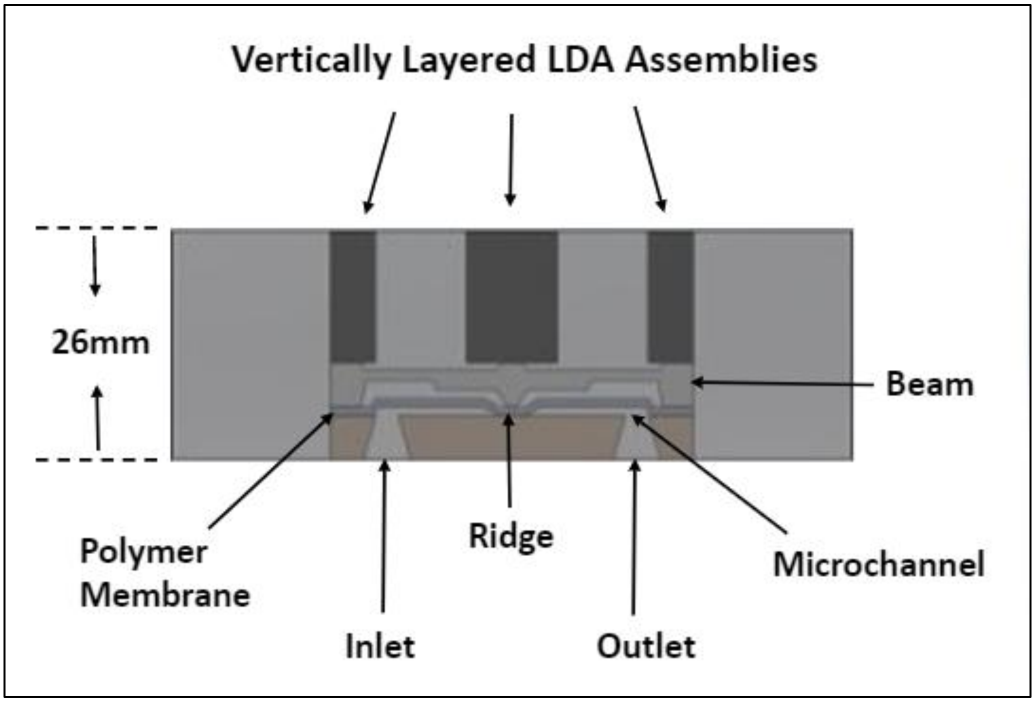


Figure 15: Light actuated microvalve prototype design

The valve design consists of three vertically orientated light driven actuators that will open the flow way when a light source is applied. This specific valve design can be classified as a normally closed microvalve. In its resting state, the fluid cannot flow due to the valve being closed. Once the light source is applied the actuators then react and allow the fluid to flow. The other components of this valve include a polymer membrane and semi-rigid beam that create the microchannel for fluid to flow through. This prototype design is assembled in between two microscope slides to encase the valve.

This design was inspired by a piezoelectric microvalve design created for integrated chemical analyzing systems (Shoji et al., 1991). In the same research paper, a normally open microvalve and a three-way microvalve were also designed. However, it was decided that the normally closed microvalve would be best suited for the LDAs. The reason for this is for when the microvalve will be in the open position only when the light source is powered on.

4.1.1 Suggested Materials

Materials suggested for fabrication of the microvalve can be broken down by each component involved in the assembly from Figure 15. The vertically layered LDA assemblies should be comprised of Process 2’s 4-layer LDA. 3D printed thermoplastic polyurethane (TPU) was chosen as the ideal material for the central beam and lower base due to its flexible material and quick manufacturability. The 26mm tall housing walls can be comprised of glass microscope slides, and the polymer membrane can be either a CNT or graphene-nanoplate polymer.

Chapter 5 Conclusions

5.1 Project Overview

5.1.1 Recommendations

Based off the experimental results, the 4-layer actuator created the largest stress values. This is due to large force values being experienced on the scale with a smaller thickness compared to the 7 and 10-layer actuators. We recommend that the 4-layer actuators are used in the microvalve to successfully actuate the valve.

5.1.2 Future Research

Light-driven actuators are one of the most promising candidates to advance the fields of soft robotics, aerospace, and medical devices. Further exploration of the electrical properties of CNT actuators paired with other polymers aside from PDMS is recommended. The fabrication process could also be refined to find an alternate method without the need for baking and degassing.

Building a physical prototype should involve further research in selecting the optimal materials for the valve, depending on its application. If used in propulsion systems, corrosion and heat resistant metals should be explored. If used in medical applications, soft hydrogels or biosafe materials are suggested. A review of the basic fluid mechanic formulas is recommended, as they will be important in making fluid and gas calculations associated with a functioning valve prototype.

The piezoelectric capabilities of a CNT fabricated microvalve can also be explored, as piezoelectric technology allows for the potential of multiple applications in a fluid based electrical control system. An example could be within dielectric cooling processes. Dielectric fluid is an electrically non-conductive liquid with high resistance to electrical breakdown. Dielectric fluids provide insulation and prevent unwanted electrical discharge in electrical systems (Croda). Dielectric cooling systems create a magnetic field which polarizes the dielectric fluid, which can actuate mechanical output depending on the piezoelectric polymer also used in the microvalve. This example can be used to simply open and close each channel of the valve.

5.2 Conclusion

This project investigated the promising research field of light driven actuators, focusing on CNT-polymer materials that will lay the groundwork for future developments in microvalve technology and piezoelectric systems utilizing CNT actuators. Our team successfully met the objectives and central goal of the project defined at its initiation. Throughout the year long duration of work, the team developed a refined LDA manufacturing process capable of producing several layered variations of CNT-PDMS actuators. Mechanical testing demonstrated the ability of each actuator to produce different amounts of mechanical force when in the presence of light, enabling the team to further analyze its stress and strain curves. This research helped the team determine the ideal layering to be used in a light driven microvalve prototype design. Our team hopes that future engineers will be able to use this research to one day develop a fully functional LDA microvalve that can replace the traditional electrical and motor driven technology used today.

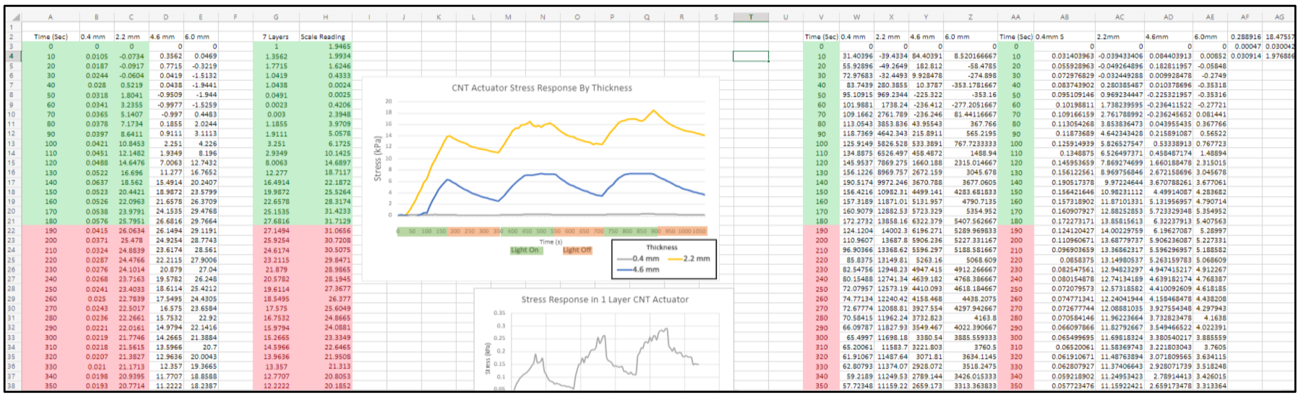
Appendix

Appendix 1: Prior Research

[‘Light Driven Actuators’ 2018 MQP Report]

[‘Optically Driven Robot’ 2021 MQP Report]

Appendix 2: Data Analysis



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