Worcester Polytechnic Institute

Major Qualifying Project

ODR

Optically Driven Robots

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Abstract

The objective of this project, optically driven robots, or light-actuated robots, was to analyze the characteristics of carbon nanotubes (CNTs) to determine their ability to replace traditional actuators within robotic systems. Our team presents a refined and optimal CNT manufacturing process for developing CNT actuators. The CNT actuators underwent experimentation to analyze their mechanical characteristics such as displacement, stress, and strain. Using the CNT actuators, we designed a robotic inchworm utilizing a CNT actuator as the inchworm's body, as well as two rigidly attached feet at 45-degrees from the CNT body. Control of the robotic inchworm is based upon an open-loop control system coupled with a MATLAB program that varies duration of light exposure directed at the CNT actuator. We report on the average displacement and velocity based upon the constructed control system for the robotic inchworm. With the current limitations of traditional robotic system hindering their ability to work in space and within medical devices such as MRIs, we believe our robotic system demonstrates the ability to help develop non-magnetic robotic systems for these various applications.

Executive Summary

Robotic systems are playing an ever-increasing role in everyday activities from work life to home life. As a result of this increasing role, many researchers have begun to explore new ways to actuate these robotic systems to allow them to work within specific environments and help eliminate power consumption. Today, robotic systems are actuated utilizing traditional systems such as motors and servos; however, this project explores new ways to actuate and control robotic systems utilizing carbon nanotubes (CNTs). CNTs provide a new and innovated construction to robotic systems eliminating the need for traditional metallic components due to their actuation based upon the presence and absence of a concentrated light source.

The team focused on four main objectives: 1) development of a CNT film manufacturing process, 2) creation of CNT actuators, 3) exploration of their mechanical properties, and 4) demonstration of control of such actuators. Development of the CNT film manufacturing process produced a repeatable procedure that synthetically developed a free-standing single-walled nanotube (SWNT) film. Utilizing the free-standing SWNT film, the team created CNT actuators using a double-sided acrylic elastomer, single-sided acrylic elastomer, and a PVC film. The CNT actuators configuration provided a flexible and rigid design allowing the actuator to retain its original shape throughout the actuation cycle. The team conducted various experiments to expose the mechanical characteristics of the CNT actuators: stress, strain, displacement, velocity, etc. Utilizing the mechanical characteristics, we developed a robotic inchworm with the CNT actuator integrated into the system. The robotic inchworm was used to demonstrate controllability of robotic systems based upon the duration of light exposure presented to the CNT actuator.

Carbon nanotubes, the basis for this project, are small structures of carbon in a cylindrical shape with special properties. CNTs were first discovered in 1952 and have continued to grow in popularity since (“Who Invented Carbon Nanotubes?”, n.d). Through experimentation, it was observed that carbon nanotubes are fibers by nature and possess a property known as Optically Stimulated Electron Emission (OSEE). OSEE is a phenomenon of releasing particles within a material when radiant light is absorbed by the material. This phenomenon enables CNTs to undergo light actuation (Chawla, 2015).

Light actuation is the process of taking the energy emitted from the photons and converting it into mechanical energy (Chawla, 2015). This conversion of energy is carried out within the material or substance that is being utilized, such as carbon nanotubes. Light actuation is being utilized to negate the need for traditional metallic materials, such as electrical wires and motors, to achieve mechanical motion (Chawla, 2015). Many applications could benefit from the implementation of light actuation, such as microrobots (Glückstad, 2017), and research in this field continues to grow. A past WPI project involved the creation of tweezers constructed of carbon nanotubes that opened and closed based on the presence of light also demonstrates the fundamentals behind light actuation (Lu, 2005).

Electromagnetic relays utilize an electromagnet to close the circuit and a spring to keep it open (Relay Basics, n.d.). Therefore, when there is an electrical signal ran through the electromagnet, a magnetic field is induced, which pulls or pushes the armature depending on the flow of the electrical signal. When the electrical signal is removed, the spring pulls the armature back to its resting position, which opens the circuit. Due to the nature and size of these relays, they are typically a bulky option and have a slower operation rate. This can prove to be a problem in systems that require a fast change of state.

LED (Light Emitting Diode) Arrays are composed of columns and rows containing individual LEDs wired in parallel. By wiring the LEDs in a parallel system, it allows for the voltage to be consistent between each component of the electrical circuit. Each LED is a semi-conductor that produces light as electricity is passed through the leads (e.g. anode and cathode). The light emitted is due to a reaction between the electrons within the LED attempting to cross the band gap between the leads (Indian Institute of Technology, 2014). This results in photons being emitted because of the energy required to pass that band gap.

The free-standing films, utilized in the CNT actuators, was the result of the team's third iteration of the carbon nanotube manufacturing process (Appendix B). The developed free-standing films were constructed in steps: 1) attach double-sided acrylic elastomer to PVC film, 2) place free-standing SWNT film onto the double-sided acrylic elastomer, 3) place single-sided acrylic elastomer on top of exposed free-standing SWNT film, and 4) trim up sides to make a cantilever actuator. The design promoted the most significant actuation while retaining flexibility for the actuator to bend but enough rigidity to retain its shape in the presence/absence of light. Various experiments were then conducted on the final iteration of the CNT actuator to explore its mechanical characteristics.

The CNT actuators underwent experimentation to analyze their displacement, stress, and strain. The displacement analysis determined the total change in position the actuator displayed when exposed to a light source. The results of the analysis presented a repeatable change in position of approximately 10 mm ± 3 mm; achieving a maximum displacement of 10.164 mm. The strain analysis presented the total change in length the actuator experienced during an actuation cycle. The team determined that the CNT actuator was able to undergo 0.3% strain given maximum light exposure. The stress analysis demonstrated the force applied to the cantilever CNT divided by the cross-sectional area of the actuator. Our team calculated the tensile stress of an actuator of size 1 cm by 4 cm to be 1126.633 kPa.

The team developed a robotic inchworm utilizing a synthetically bent CNT actuator. The system underwent various experiments to determine the optimal feet material and configuration in a controlled environment. The final feet configuration was constructed using tin at two 45-degree angles, which experimentally presented 5.03mm of displacement, which was significantly larger than the other configurations. For testing, the team suspended the robotic inchworm in a testing apparatus to control its exposure to a light source.

The testing apparatus was composed of three LED arrays, a piece of acrylic, and multiple VEX parts. The testing apparatus was used to concentrate the light source onto the robotic system and manipulating the environment to promote forward motion. Accompanying the testing apparatus, the team developed an open-loop control system. The open-loop control system utilized an electromagnetic relay, three LED arrays, and an Arduino Mega. The system's reference signal was manipulated using a MATLAB program that sent a high (5-volt) signal and low (ground) signal depending on the elapsed time. We determined the time intervals were determined based upon the desired actuation cycle needed for the control setting. Utilizing the control system and testing apparatus, the team developed controlled experiments to determine the displacement and velocity of the robotic system.

The team measured the average velocity achieved by the robotic inchworm, as well as the average displacement for four different durations of light exposure: 5 seconds, 10 seconds, 15 seconds, and 20 seconds. We determined that the robotic system's average velocity was 0.2465 mm/sec ± 0.0065 mm/sec. In addition, the team determined the average displacement of the robotic inchworm to be 1.02 mm after 5 seconds and 5.03 mm after 20 seconds of exposure to a light source.

This project explored the relatively new research field of smart materials focusing primarily on CNTs, which laid the foundation for future developments of robotic systems utilizing CNT actuators. The team developed and refined a manufacturing process capable of producing free-standing SWNT films that were utilized to create carbon nanotube actuators that responded to the presence and absence of light. The robotic inchworm developed by the team demonstrated the ability to control these actuators, enabling integration into future robotic systems. Our team hopes that robotic systems will be able to be developed without use of magnetic mechanisms with carbon nanotube actuators in their place, opening a whole range of possibilities using non-magnetic robots.

Future research involving this project could include the implementation of computer vision and/or creation of a hand-like robotic manipulator. Computer vision would allow for the development of a closed-loop control system. With the development of a closed-loop control system, future teams could demonstrate the ability to control the robotic inchworm to significantly small displacements depending on the resolution of the camera. Future MQP teams can expand upon the team's procedures and results to develop a robotic manipulator that utilizes five CNT actuators for its fingers. To control this system, the team could employee the use of lasers focusing it directly onto each individual CNT actuator allowing them to displace about their rigid attachment point separately.

Acknowledgements

We are extremely grateful and thankful for all of those who have assisted in the development of this project. Above all, we would like to thank our advisors, who continually guided and focused our efforts towards the desired end goal. Without the assistance and support from you, we would not have achieved our goals for this project.

Secondly, we had the chance to meet two wonderful individuals: Aref Aasi and Sadegh Mehdi Aghaei, PhD students in the Small Systems Lab, who were able to provide us with the necessary knowledge and background necessary for developing the light actuators for the robotic systems. Additionally, we would like to thank WPI's Higgins Labs, Robotics Laboratory, Foisie Makerspace, and Washburn Shops for allowing us to utilize your equipment to develop and build the robotics systems.

Finally, we would like to extend thanks to everyone else who helped us along the way. Without each and every one of you, this project would not have happened.

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Chapter 1

Introduction

Robotic systems are playing an ever-increasing role in everyday activities from work life to home life. As a result of this increasing role, many researchers have begun to explore new ways to actuate these robotic systems to allow them to work within specific environments and help eliminate power consumption. Magnetic Resonance Imaging (MRI) surgeries are relevant example: currently there are non-magnetic robotic systems capable of conducting precise surgeries within such medical devices since robotic systems are actuated utilizing traditional systems such as motors and servos. An alternative to traditional actuators is carbon nanotubes (CNTs). CNTs are an appealing alternative due to their new and innovated construction to robotic systems eliminating the need for traditional metallic components due to their actuation based upon the presence and absence of a concentrated light source.

Despite these benefits, CNT actuators are in a relatively new research field of smart materials requiring more research before their true capabilities can be determined within the robotic industry. We hypothesize that if researchers can continue building upon pre-existing research, then non-traditional actuated robotic would provide engineers, scientists, and many others the ability to utilize robotic systems in a variety of new applications. Motivated by this hypothesis, the project describes the development of a mobile robotic system actuated utilizing CNTs. We demonstrate the ability to control the robotic system utilizing a concentrated light source and a pre-determined duration of light exposure, as well as the mechanical characteristics of the CNT actuators. In the following section, our team discuss the motivating examples for this project and then describe the objectives behind the development of our mobile robotic system.

1.1 Motivations

In this section, our team addressed the motivating examples for the work conducted throughout the duration of the report. These examples address multiple areas such as the space and medical industries.

1.1.1 Medical Robotics

One motivation linked to the work conducted for this project is the current state of robotic systems within the medical field. Today, robotic systems are beginning to play an ever-increasing role in various surgical procedures, such as manipulating surgical instruments through one or more small incisions (Gyles, 2019). One field of medicine that has yet to benefit from the implementation of robotic systems is Magnetic Resonance Imaging (MRI). MRI machines utilize strong magnets to take high quality of a patient's body. Due to the use of magnets, metal is not permitted inside an MRI machine because it will impact the machine and the quality of the images produced, and can even hurt the patient (Hargreaves, n.d.). This predicament limits robot's ability to work within an MRI machine because traditional actuators contain metallic components. This project explores the potential implementation of robotic systems that employee carbon nanotube (CNT) actuators, which can be used to develop non-magnetic systems. This development presents a compliant robotic system that could be integrated with MRI technology.

1.1.2 Space Robotics

The second motivation linked to the work conducted is the current state of robotic systems within the space industry. Robotic systems are making significant strides in the field of space exploration; however, have limitations. These robots are running on a finite power supply and have a certain lifespan until the robots are decommissioned. In space, traditional motors and manipulators found in the robotic systems are powered by batteries, which correlates directly to the length of the mission being conducted. This limitation requires robotic systems to be redeveloped after the lifespan expires. This project explores the development of hybrid robotic systems that could help extend the lifespan of robotic systems in space. One example of this development could be the employment of a CNT manipulator that utilizes the sun's concentrated light waves by various mirrors to flood these actuators to produce mechanical actuations. By utilizing a seemingly endless supply of light, these actuators will not need to use battery power, thus allowing the rover or robot to use that battery power elsewhere, therefore extending mission times. These longer mission times would be very beneficial in the field of space exploration and allow us to continue exploring the endless universe. For these reasons, carbon nanotube actuators implementation into space applications was a major motivator for this project.

1.2 Objectives of Major Qualifying Project

For the extent of this project, our team developed a list of objectives to satisfy Worcester Polytechnic Institute’s Requirements for the Major Qualifying Project (MQP). These objectives included the optimization of the CNT manufacturing process, the development of CNT actuators, an exploration of their mechanical characteristic, and a demonstration of the controllability of these actuators. This section of the paper will discuss these objectives in detail.

The first objective of the project was to optimize the CNT manufacturing process to produce free-standing SWNT films. Our team studied previous processes conducted with a silicon wafer and modified it to fit the project’s needs. Discussed within the paper, the team created a refined and optimized process that produced free-standing SWNT films in a practical and reproducible way. These free-standing SWNT films allowed the team to create the CNT actuators, the basis for the project.

The second objective of the project was to develop CNT actuators that respond to the presence and absence of a light source. The CNT actuators serve as a replacement to traditional actuators. Therefore, these actuators were required to be able to be a source of mechanical actuation. In addition, actuators needed to be flexible, reproducible, and effective. The flexibility of the actuators gives them the ability to produce the mechanical actuation sought. The reproducibility of the actuators allows them to be a practical replacement to traditional actuators since robotic systems typically contain more than one actuator. The effectiveness of the actuators, similar to the reproducibility, allows them to be a practical replacement to traditional actuators by producing the mechanical actuation needed within a robotic system. These three characteristics define the second objective of the research project.

The third objective of the project was to explore the mechanical characteristics of the CNT actuators. By exploring the mechanical characteristics of the actuators, the team developed an understanding of the possibilities related to the actuators. Through calculating the stress and strain of the actuators, the team classified the material and compare it to other materials. The team also measured the displacement of the actuator, which gave insight into the integration of these actuators into robotic systems. This objective demonstrated the characteristics of the CNT actuators for designing a robotic system.

The fourth objective of the project demonstrated the controllability of actuators within a robotic system. To effectively be a replacement for traditional motors within a robotic system, these actuators needed to be controlled. Through developing a robotic inchworm using one of the CNT actuators, the team was able to control the exposure of a light source experienced by the robotic system. Controllability is a defining factor of any robotic system and the robotic inchworm demonstrated just one example of possible robotic systems that utilize CNT actuators.

As robotic systems are continuingly being integrated into the world, the completion of these four objectives allowed the team to produce an MQP to advance current robotic systems and the field of science.

1.3 Paper Outline

The outline of this paper is as follows:

Background: Carbon Nanotubes and Optical Manipulation discusses the background knowledge associated with this research project. We discuss the field of nanotechnology and its many applications and possibilities. We analyze past WPI projects and research projects that directly correlate to our own research. We discuss the basis of CNTs, and the properties associated with optical actuation. In addition, we discuss the research conducted on the electronics associated with the robot inchworm.

Carbon Nanotube Manufacturing outlines the various steps the team took to construct the free-standing single-walled nanotube (SWNT) films utilized in CNT actuators. We discuss the goals and tasks associated with the manufacturing of CNTs actuators. Furthermore, we explain the procedures and downfalls of our first two iterations of manufacturing CNTs. The team describes the final iteration of our manufacturing procedures that produced the free-standing SWNT films utilized for the CNT actuators. Finally, we discuss the construction of the CNT actuators and the various mechanical characteristics associated with these actuators.

Robotic Inchworm presents how the team integrated the CNT actuators into a robotic system and demonstrated control of the system. The team describes the procedures and methods to develop the robot inchworm utilizing the CNT actuators. In addition, we analyze the various iterations of the robotic inchworm that was developed. Finally, the team presents the measurements taken while testing the robotic inchworm and the extent of controllability achievable with these CNT actuators.

Conclusion and Future Work review the conclusions drawn from this project and the potential for future MQPs and research that could be done with CNT actuators.

Chapter 2

Background: Carbon Nanotubes and Optical Manipulation

Before approaching this project, it was fundamental to get a better understanding of the concepts and materials that will be utilized throughout the project. Furthermore, it was imperative to learn about the past experiences that have occurred throughout previous projects to learn where the project can improve or develop a new technology within the research field. The team's research can be seen below on important topics related to the project.

2.1 Nanotechnology

2.1.1 Description

Nanotechnology is science, engineering, and technology conducted at the nanoscale, primarily between 1 to 100 nanometers. This technology can be used across all science fields, such as chemistry, biology, physics, material science, and engineering. Nanotechnology is a relatively new field of science, only gaining leverage with a talk given by Richard Feynman titled "There's Plenty of Room at the Bottom". Feynman discusses the first ideas and concepts behind nanoscience and nanotechnology by mentioning that scientists would one day be able to manipulate individual atoms and molecules (Feynman, 1959). The term "nanotechnology" was first used by Professor Norio Taniguchi in 1974 (Bayda et al, 2019). Modern nanotechnology did not officially begin until the invention of the scanning tunneling microscope in 1981. With this invention, nanotechnology began to rapidly progress and continues to.

2.1.2 Current & Theoretical Applications

There are many different applications of nanotechnology, both in-practice and theoretical. One form of nanotechnology being utilized today is superhydrophobic coatings. These coatings are developed utilizing nanotechnology and can repel water molecules and leave the surface completely dry. These coatings are being used on car windshields, rain/hiking boats, and many other technologies (National Nanotechnology Initiative, n.d.). A theoretical application of nanotechnology is drug delivery. Empowered with nanotechnology, this type of technology would allow scientists to deliver the proper medicine/drugs to an infected area of the body that is not easily accessible otherwise. A prime example is in treating cancer cells. By utilizing nanotechnology, these cancer cells can be detected, and the proper preventive action can be taken to both kill the cancer and prevent it from spreading (National Nanotechnology Initiative, n.d.).

For our project, we will focus on nanotechnology in terms of light actuation. By capitalizing on the multiple phenomenon that occur at a nanoscale, a piece of material can be developed that responds to the presence and absence of light. This phenomenon and application of such technology is further discussed later in the paper.

2.2 Light Actuation

2.2.1 Description

Light actuation, also known as optical actuation, is the process of taking the energy emitted from the photons and converting it into mechanical energy (Chawla, 2015). Since the energy within the photons falls under the Law of Conservation of Energy, the shorter the wavelength and the greater the frequency, the greater the amount of energy that has the potential to be converted into a mechanical actuation. Typically, this conversion of energy is carried out within the material or substance that is being utilized, such as crystals, nanotubes, and polymers just to name a few. The goal of the research field is to develop a way to actuate systems without the need for traditional metallic materials such as electrical wires and motors. For example, this is relevant to processes such as Magnetic Resonance Imaging (MRI) because there is currently no way to do operations while a patient is being scanned to make the surgery easier.

2.2.2 Past WPI Projects

Looking at previous projects allowed for the team to gain insight on manufacturing processes, design considerations, and requirements for light-actuated systems.

An optically driven gripper was developed at WPI in the Small Systems laboratory. Its purpose was to demonstrate the mechanical capabilities of an optical actuator through the manipulation of small objects. This project was able to overcome fundamental limitations of light actuators, such as high voltages and using electrochemical solutions (Lu, 2005). By proving that these limitations are no longer a significant barrier to the technology, it presents the possibility of stand-alone technologies that can be remotely light actuated. Notably, these light actuators had the ability to reach strain measurements of "0.01%-0.3% elastic strain generated due to electrostatic and thermal effects under visible light intensities of 5-120 mW/cm^2" (Lu, 2005). This is a relevant statistic to take into consideration while the team is developing light actuators.

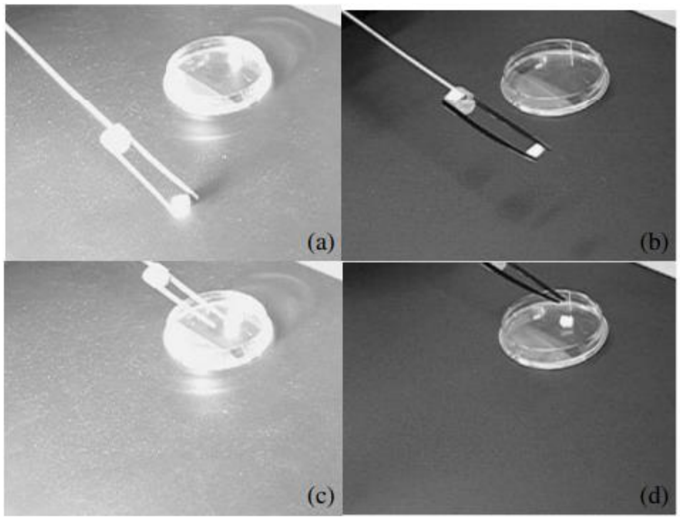

Figure 2.1 Simple Demonstration of a Two-Actuator Gripper Demonstrated in Optically Driven Nanotube Actuators by Shaoxin Lu and Balaji Panchapakesan.

2.2.3 Current & Theoretical Applications

Additionally, looking at current and theoretical applications will allow the team to gain insight on manufacturing processes, design considerations, and requirements for light-actuated systems within the real world.

2.2.3.1 Light-actuated Microrobots

The light-actuated microrobots (LAM) were developed to avoid the maneuverability problem of nanoparticles, which are difficult to control (Glückstad, 2017). These LAMs are able to be designed to the specific application they are being utilized within; however, the ones that were developed for this project are a hollow transport microrobot (Figure 2.2). By controlling each microrobot with propagating beams, which "traps each spherical handle," the research team was able to navigate them to a desired location to pick up materials and transport that material to another area of interest (Glückstad, 2017). This was an interesting project because if the research team can perfect and accurately control the microrobots within a living organism’s body, they could use this technology to deliver pharmaceutical drugs into the body, conduct surgery, and be applied in many other medical applications.

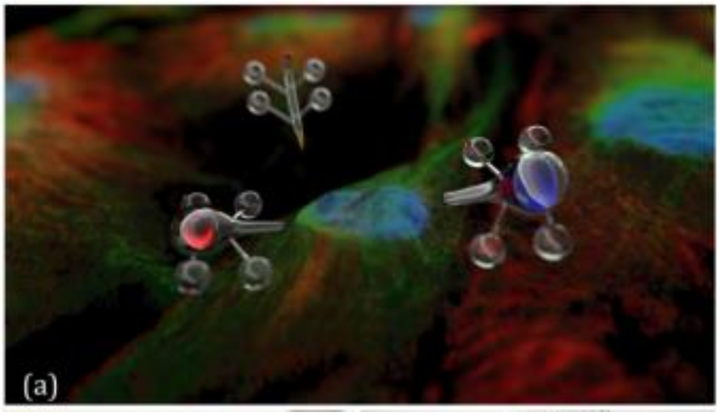

Figure 2.2 Light-Actuated Microrobot Probing a Cell Shown in Light-Actuated Microrobots for Biomedical Science by Jesper Glückstad, et al.

2.2.3.2 Liquid Crystalline Soft Robotic Caterpillar

This soft robot was developed using liquid crystalline elastomers (LCEs), which are smart materials that can have large deformations due to light exposure (Rogóż, 2016). These large deformations were the fundamental basis in which the soft robotic caterpillar was developed. By controlling the deformation pattern using a concentrated laser, the research team was able to control the walk of the caterpillar along flat surfaces (Rogóż, 2016). Therefore, the research team was able to mimic the walk of a caterpillar by focusing the laser on small parts of the crystalline structure as the laser slowly moved across the structure from the back to the front. This project demonstrated the possibility of remotely actuating light-sensitive robotic systems through focused beams of light.

Figure 2.3 Soft Robotic Liquid Crystalline Elastomer Caterpillar from Light-Driven Soft Robot Mimics Caterpillar Locomotion in Natural Scale by Mikolaj Rogóż, et al.

2.2.3.3 Light-triggered Artificial Flytrap

The optical flytrap is a fiber-tip device that can grip onto any micro-sized object from a cube to a sphere (Wani, 2017). The actuation of the flytrap is induced as the object gets within the range of the light being emitted at the center of the flytrap, which reflects the light downwards onto the material causing an actuation to grip the object. Notably, the force produced by the actuators ranges from 0 to 225 μN depending on the intensity of the light flooding the light actuator (Wani, 2017). This is a relevant statistic that the team will take into consideration when developing the light actuators for the project.

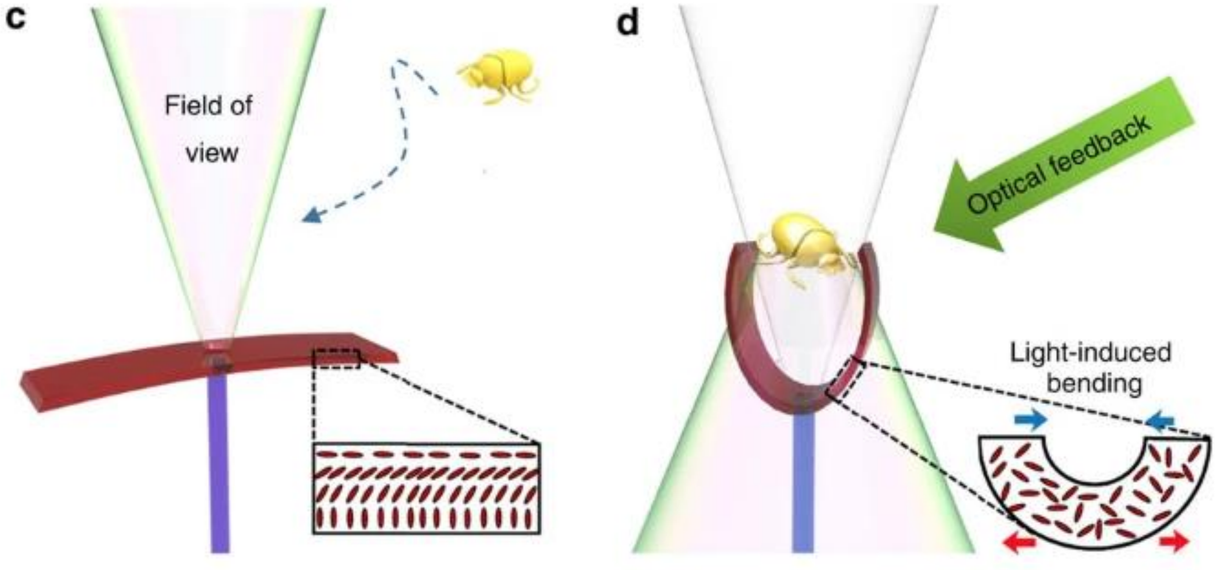

Figure 2.4 Light-Triggered Artificial Flytrap Exhibited in a Light-Driven Artificial Flytrap by Owies Wani, et al.

2.3 Carbon Nanotubes

2.3.1 Description

Carbon Nanotubes (CNTs) were first discovered in 1952 by two Russian scientists, L. V. Radushkevich and V. M. Lukyanovich, and measured at 50 nanometers in diameter ("Who Invented Carbon Nanotubes?", n.d). At first, they were just seen as a small structure of carbon in a cylindrical shape (Figure 2.5). However, they were tested and observed through experiments, which determined that these structures were a fiber in nature, as well as semi-metals or semiconductors ("Who Invented Carbon Nanotubes?, n.d). Although these CNT may be manufactured as metals, they are non-magnetic. Additionally, through experimentation, it was determined that CNTs had the property known as Optically Stimulated Electron Emission (OSEE). OSEE, also known as the photoelectric effect, is the phenomenon of releasing particles within a material when radiant light is absorbed by the material (Chawla, 2015). Alternatively, this property can also be seen as the releasing of electrons from the surface of the CNTs when light is directed onto the materials. Upon discovery of the OSEE property, scientists began to experiment with ways to utilize CNTs to solve a plethora of problems. The primary use that is highlighted and focused upon within the scope of this project is light actuators.

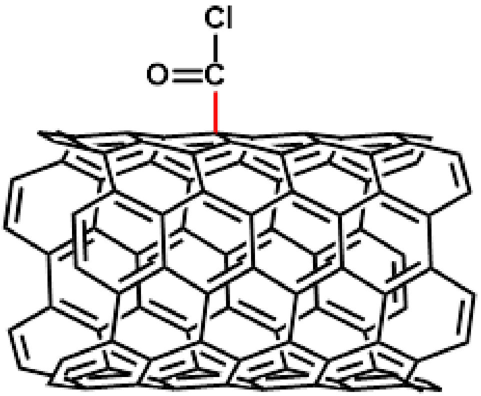

Figure 2.5 Carbon Nanotube

Light actuators use Single-Walled Nanotubes (SWNTs), a CNT variation with 1 nanometer diameter tubules (Yanagi, 2014), to convert electrical energy directly to mechanical energy. These actuators mimic a natural muscle because "the millimeter-scale actuators are assemblies of millions of individual nanotube actuators processed into macroscopic length scales and bonded to an acrylic elastomer sheet to form an actuator that has been shown to generate higher stress than natural muscles and higher strains than high-modulus piezoelectric materials" (Lu, 2005). Furthermore, these actuators only require a small voltage to complete its actuation compared to other piezoelectric materials. These characteristics make CNT light actuators desirable for many optically actuated systems.

2.3.2 Current & Theoretical Applications

The projects mentioned above in 2.2.2 and 2.3.3, the light-actuated flytrap and the nanotube gripper, utilized carbon nanotubes for mechanical actuations because of a flooded light source. These are just two applications that are possible with the integration of carbon nanotubes and utilizing their specific chemical properties.

2.4 Electronics Research

The scope of the project was to incorporate light actuators into a robotic system in place of traditional actuators such as motors; therefore, the electronics of the system defined many of the characteristics of the final design for the robotic system. Furthermore, it was imperative to consider the light, power, and control requirements of the system. Researching into the electronic components allowed for the creation of a final circuit diagram for the robotic system, which incorporated all these requirements.

2.4.1 LEDs & LED Arrays

LED (Light Emitting Diode) Arrays are composed of columns and rows containing individual LEDs wired in parallel. By wiring the LEDs in a parallel system, it allows for the voltage to be consistent between each component of the electrical circuit. Each LED is a semi-conductor that produces light as electricity is passed through the leads (e.g. anode and cathode). The light emitted is due to a reaction between the electrons within the LED attempting to cross the band gap between the leads (Indian Institute of Technology, 2014). This results in photons being emitted because of the energy required to pass that band gap. LEDs can produce various wavelengths of light (i.e., color of light) by changing the material that is used during the manufacturing process. LEDs are made up of the following basic components that can be seen in the figure below (Indian Institute of Technology, 2014):

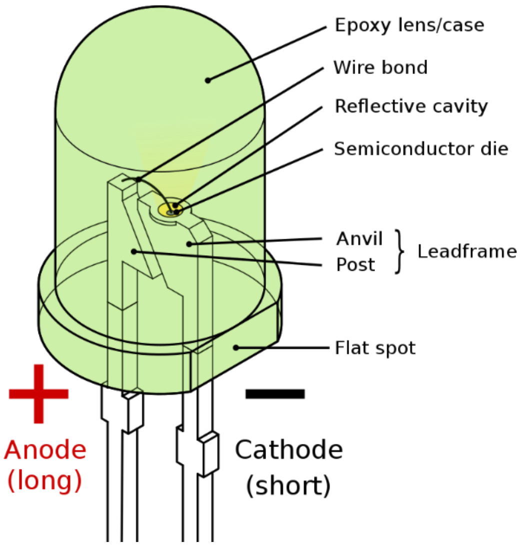

Figure 2.6 LED Diagram

While LEDs are widely used for many different applications due to their low power consumption, size, and maintenance, LEDs are susceptible to damage if the current or voltage is too high for the specific LED. The correct voltage and current ranges can be found on the individual LED datasheets.

2.4.2 Relays

On a basic level, a relay is an electrically operated switch that changes positions between closed and open based upon the input signal. This provides a sense of control with the electronic circuit since the relay can be operated using a microcontroller and an electrical signal. There are two main types of mechanical relays: electromagnetic and reed relays. Each relay uses a different system to open and close the switch.

Electromagnetic relays utilize an electromagnet to close the circuit and a spring to keep it open (Relay Basics, n.d.). Therefore, when there is an electrical signal ran through the electromagnet, a magnetic field is induced, which pulls or pushes the armature depending on the flow of the electrical signal. When the electrical signal is removed, the spring pulls the armature back to its resting position, which opens the circuit. Due to the nature and size of these relays, they are typically a bulky option and have a slower operation rate. This can prove to be a problem in systems that require a fast change of state. The mechanism can be modeled in Figure 2.7.

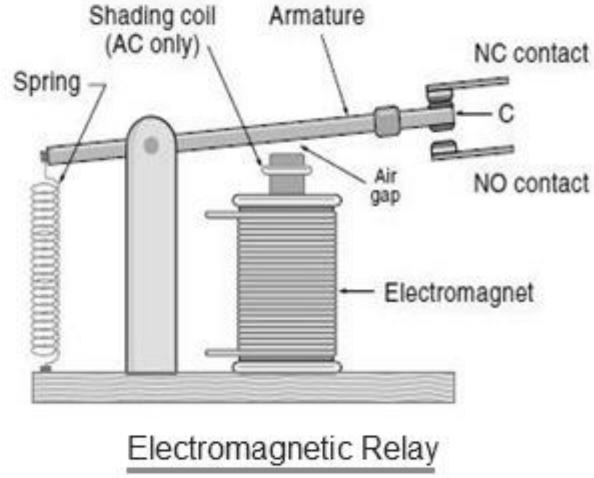

Figure 2.7: Electromagnetic Relay Diagram Detailed in the Article, Relay Basics.

Reed relays utilized ferromagnetic leads with nitrogen encapsulated within the tube to reduce the chance of erosion (Relay Basics, n.d.). Unfortunately, reed relays still require a magnetic field to close the circuit, which means the tube must be enclosed in an external solenoid or brought into the range of an external magnet (Figure 2.8). Outside of the need for an external magnetic field, reed relays are a faster option due to their easily magnetizable leads (Relay Basics, n.d.). This allows for systems to change state quickly with a minimal delay.

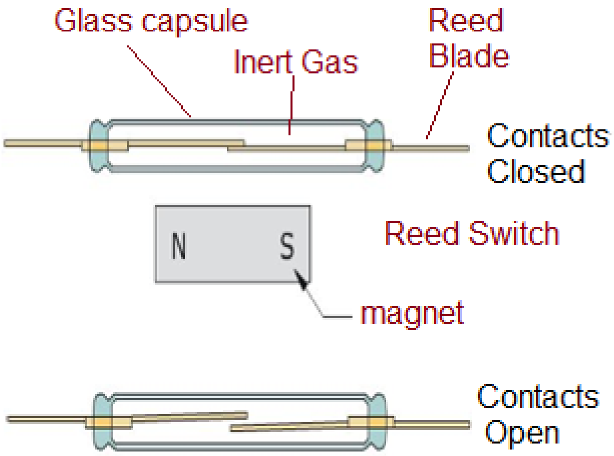

Figure 2.8: Reed Relay Diagram Presented by the Article, Relay Basics.

Chapter 3

Carbon Nanotube Light Actuators

Carbon nanotube (CNT) light actuators are the fundamental foundation of our optically driven robotic system. These actuators allow for the team to replace motors on a typical robotic system with a carbon nanotube actuator that is receptive to light. The goal of this section was to research and develop our own manufacturing techniques for developing the CNT actuators to meet the specifications for our robotic system.

3.1 Methodology & Materials

3.1.1 Task Specifications

For this research MQP, our team approached the project in stages. Each stage had their own goals that were necessary to advance our project into the next stage. In the first stage, the team was focused on developing a process for manufacturing light actuators. These light actuators were an essential step before being able to design and construct a robotic system that utilizes the CNT actuators instead of traditional actuators. The goals of this stage of the research MQP are as follows:

- Develop an optimal procedure for a free-standing SWNT film
- CNT actuator utilizes PVC film and elastomer
- Actuation from a light intensity of 60mW/cm^2 or greater
- Develop a way to protect SWNT film from outside environmental factors
- After actuation, return to original length and orientation
- Desired displacement of 5 mm
- Desired max strain of ~0.3% or greater

Unlike a traditional robotic system, where motors or servos actuate the robotic platform, the optically driven robotic system requires the CNT actuators for movement. With the transition to CNT actuators, our team deemed the goals for the first stage to be realistic and necessary to promote motion within our robotic system. However, each goal could not be completed at the same time. Therefore, the team sat down and developed an order that would allow for an effective and efficient completion of manufacturing the CNT actuators.

Our team decided to first work to develop a refined and optimal process of creating a free-standing SWNT film. Throughout the refinement process, our team first started with an initial manufacturing process, then worked to develop a final optimal manufacturing process.

Upon completion of the refined and optimal manufacturing process of free-standing SWNT films, experiments were completed by the team to determine the best configuration of the PVC film and elastomer to obtain the desired stress and displacement. An additional constraint that was observed by the team was the CNT actuator's ability to return to its original shape and length upon removal of the light source.

3.1.2 Work Schedule

During the summer, the team primarily focused upon research and exploration of past projects within similar fields to this research MQP. The research allowed the team to learn background information about CNTs, including their properties, theoretical applications, and general manufacturing techniques. Furthermore, the background information laid the foundation for the research MQP by providing the team with an understanding of the strengths, weaknesses, and opportunities of utilizing the CNTs. With this in mind, the team was able to approach the project in the most effective way possible.

In the beginning of A-term, the team learned the typical process of developing a SWNT film on a silicon wafer. Throughout the duration of A-term, the team worked to develop a new process for developing the light actuators that met the specifications defined above. Due to the lack of research on the subject, our team experimented with new manufacturing techniques in iterations to get the final process.

Throughout the duration of B-term and the initial weeks of C-term, the team finalized the last iteration of the process streamlining the manufacturing procedures for SWNT free-standing films. Most of B-term was utilized for testing the light actuators to observe the mechanical characteristics of the light actuators and describe their behavior when exposed to a light source. The data recorded was used for designing of our robotic system that utilized the light actuators.

3.1.3 Iteration 1

The team conducted an experiment for the general procedure of creating a SWNT film on a silicon wafer. The carbon nanotubes (CNTs) used in this procedure were commercially obtained through a pulsed laser ablation process and purified with nitric acid reflux, cycles of washing and crossflow filtration. A solution of 85mL of deionized (DI) water, 15mL of Sodium Dodecyl Sulfate (SDS), and a calculated concentration of a diluted SWNT solution within N-Methyl-2-pyrrolidone (NMP) was agitated in a sonicator for 20 minutes. The sonication process evenly disperses the CNTs within the liquid solution. In parallel, a silicon wafer, with diameter of 104.6 mm, was soaked for five minutes in acetone, isopropyl alcohol (IPA), and DI water each, in respective order. The wafer was dried using pure nitrogen (N2) and placed on a hot plate set to 120ºC. The agitated solution underwent vacuum filtration through a Polyvinylidene difluoride (PVDF) membrane. After filtration, the filtration membrane with the SWNT film was gently rinsed in acetone, isopropyl alcohol (IPA), and DI water, respectively. The rinsed membrane was manually pressed and transferred to the silicon wafer through an evaporation process of acetone. This process can be seen in Appendix A of the project report.

3.1.4 Iteration 2

Iteration two involved a similar procedure but the materials were changed, and the acetone was removed from the procedure. Therefore, the solution was developed using a solution of 85mL of deionized (DI) water, 15mL of Sodium Dodecyl Sulfate (SDS), and a calculated concentration of a diluted CNT solution within N-Methyl-2-pyrrolidone (NMP). The combined solution was agitated in a sonicator for 20 minutes. Unlike before, the silicon wafer was replaced with a synthetically developed polyvinyl chloride (PVC) wafer. Like iteration one, the wafer was soaked for five minutes in IPA and DI water respectively and dried with pure Nitrogen (N2). Again, at the completion of the solution’s agitation process, the team conducted the vacuum filtration process of the solution and finalized it by rinsing the filtration membrane with IPA and DI water respectively. Finally, the membrane was gently rinsed in IPA, and DI water and transferred to the PVC Film Wafer through a manual press and left to dry overnight.

3.1.5 Iteration 3

Iteration three resulted in the production of a free-standing SWNT film. 16mg of CNTs was dispersed in 100mL of IPA. The solution was agitated for 20 hours to obtain an even CNT distribution within the IPA. Then, the solution underwent vacuum filtration to transfer the CNTs onto a filter. Next, 20mL of IPA was passed through a Polytetrafluoroethylene (PTFE) membrane to wet the filter. Following the IPA, the agitated CNT solution was immediately filtered using vacuum filtration. Lastly, the membrane with the SWNT film is gently rinsed in IPA and DI water, then placed in a petri dish to dry for two hours before removing the free-standing SWNT film from the filter. This was the final process that was developed for developing the CNT actuators for this research project (Appendix B).

3.1.6 CNT Actuators

A cantilever CNT actuator was manufactured by rigidly attaching the free-standing SWNT film to a double-sided acrylic elastomer, which was attached to a 100 µm thick PVC film. The SWNT film was covered with a single-sided acrylic elastomer to protect the film. The diagram below demonstrates the shape and design of the CNT actuator as described above.

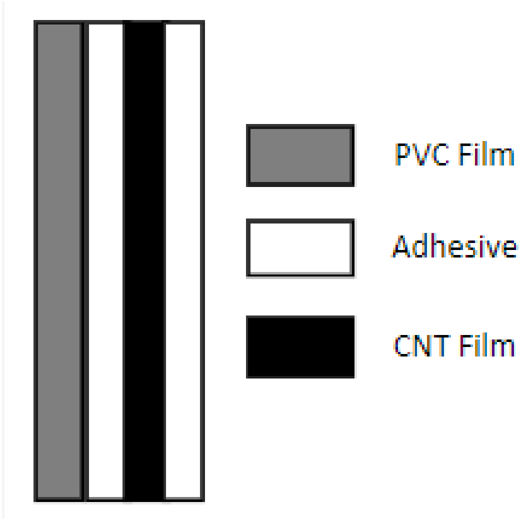

Figure 3.1 Carbon Nanotube Actuator Diagram

3.2 Results & Discussion

The following section discusses the various iterations conducted in order to create the carbon nanotube film to construct the light actuators.

3.2.1 Iteration 1

Discussed in section 3.1.3, a silicon wafer was utilized to create a carbon nanotube film. Pictured in Figure 3.2 are the results from this process. This iteration resulted in a cleanly transferred SWNT film, confirmed by microscopic inspection. However, the silicon wafer is rigid and hard to work with. To construct the carbon nanotube actuators, a material must be used that is able to bend and retain its shape. The material must also be able to be altered to a specific shape. The silicon wafer is neither bendable nor shapeable, making it a poor candidate in constructing our carbon nanotube actuators.

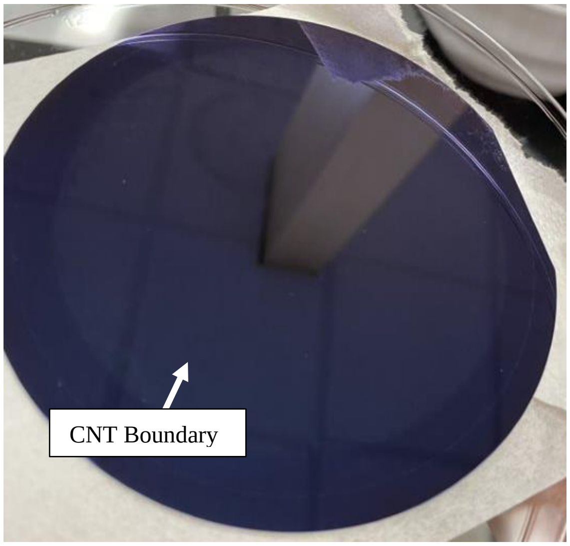

Figure 3.2 Silicon Wafer with SWNT Film

Iteration 1 was the initial process for developing a SWNT film. The team used this iteration as a practice manufacturing experiment to learn the general procedures related to transferring SWNT films to materials. This iteration allowed the team to take away information necessary for future iterations. Lastly, the team deemed the silicon wafer a nonviable material for the construction of the CNT actuators.

3.2.2 Iteration 2

From section 3.1.4, a very similar process to iteration 1 was conducted by replacing the silicon wafer with a polyvinyl chloride (PVC) sheet (pictured in Figure 3.3). This iteration resulted in a poorly transferred SWNT film, confirmed by visual and microscopic inspection. The film had visible cracks around the edges of the film and various holes within the film. The PVC sheet was able to bend while retaining its shape. However, the SWNT film transfer process utilizing a PVC sheet results in a poorly transferred SWNT film, making the material a poor candidate in constructing our carbon nanotube actuators.

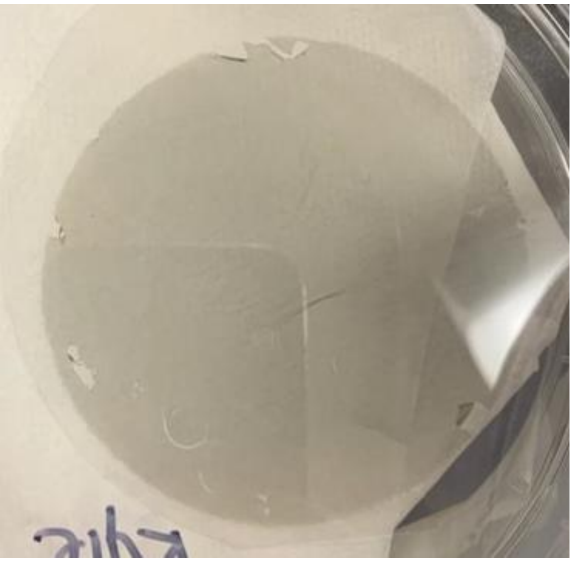

Figure 3.3 PVC Wafer with SWNT Film

Iteration 2 was the intermediate process for developing a SWNT film. This iteration demonstrated the ability to utilize a variety of materials for the development of the SWNT film. The team used this new information and lab practices to move forward in finding a subsidiary material or process that would provide a clean SWNT film. This was the basis the team utilized when completing future iterations.

3.2.3 Iteration 3

Explained in section 3.1.5, a free-standing SWNT film was created to develop carbon nanotube actuators (pictured in Figure 3.4). This iteration resulted in a cleanly transferred SWNT film, confirmed by visual and microscopic inspection. The resultant SWNT film was brittle and dense. The team attached the film to a PVC sheet utilizing a double-sided acrylic elastomer tape. After undergoing testing, the actuator demonstrated the ability for the film to bend while retaining its shape. We deemed the free-standing film the best candidate for constructing our CNT actuators.

Figure 3.4 Free-Standing Carbon Nanotube Film

Iteration 3 was the final process in the refining and optimizing the manufacturing procedures for SWNT free-standing films. The team determined a suitable SWNT film that was used in construction of CNT actuators despite the significant time commitment for the preparation and completion of the experiment. We used this process to create various SWNT free-standing films throughout the project for analyzing the mechanical characteristics and developing the robotic inchworm.

3.2.4 CNT Actuators

A carbon nanotube actuator was created utilizing the free-standing SWNT film, a PVC sheet, double-sided acrylic elastomer, and single-sided acrylic elastomer (Pictured in Figure 3.5). Multiple experiments were conducted to determine the elasticity and shape retention of the cantilever CNT actuator. These experiments included exposing the actuator to a commercial flood light in a light-absent space. The preliminary experiments concluded that the actuator could or could not respond to the concentrated light source. We would utilize or discard the CNT actuator depending on its ability to respond to the concentrated light source.

Figure 3.5: Carbon Nanotube Actuator

The team developed a few CNT actuators that were deemed satisfactory based upon their response to a concentrated light source. These CNT actuators were used to invoke motion for the different designs of the robotic inchworm. This was meant to demonstrate the ability to replace traditional actuators like motors and servos with these CNT actuators for many different applications.

3.3 Modeling & Analysis

Modeling and analysis of a cantilever CNT actuator was used to observe and calculate its mechanical characteristics. For the scope this research project, it was necessary to determine the following mechanical characteristics for the CNT actuator: strain, stress, and displacement. The analysis is presented in the following sections.

3.3.1 Displacement Analysis

Displacement is the movement of an object from its current place or position. In order to observe this movement, an experiment was developed with a dark box, Newport 1815-C light intensity meter, three LOHAS 100W LED arrays, digital stopwatch, metric ruler, and a digital camera. The dark box was configured as a rectangular prism with a clamp extending downwards from the ceiling and the light intensity meter located in the corner of the box. The clamp was used to anchor the light actuator into place and the digital camera was incident normal to the side of the actuator. Finally, the three LED arrays were each placed 25 mm away from the CNT actuator with one array directed on the PVC film and two directly on the SWNT film side of the actuator depicted in Figure 3.1.

For testing, a light intensity of 151.87 mW cm^{-2} was utilized to actuate the CNT actuator for three cycles. Each cycle was broken down into 40 second intervals: 20 seconds for the light to be on and 20 seconds for the light to be off (timed with the digital stopwatch). Within the light exposure period, the displacement of the cantilever CNT actuator was measured utilizing the metric ruler from the live camera feed. Once the data was recorded, it was reported in a graphical format depicted in Figure 3.6.

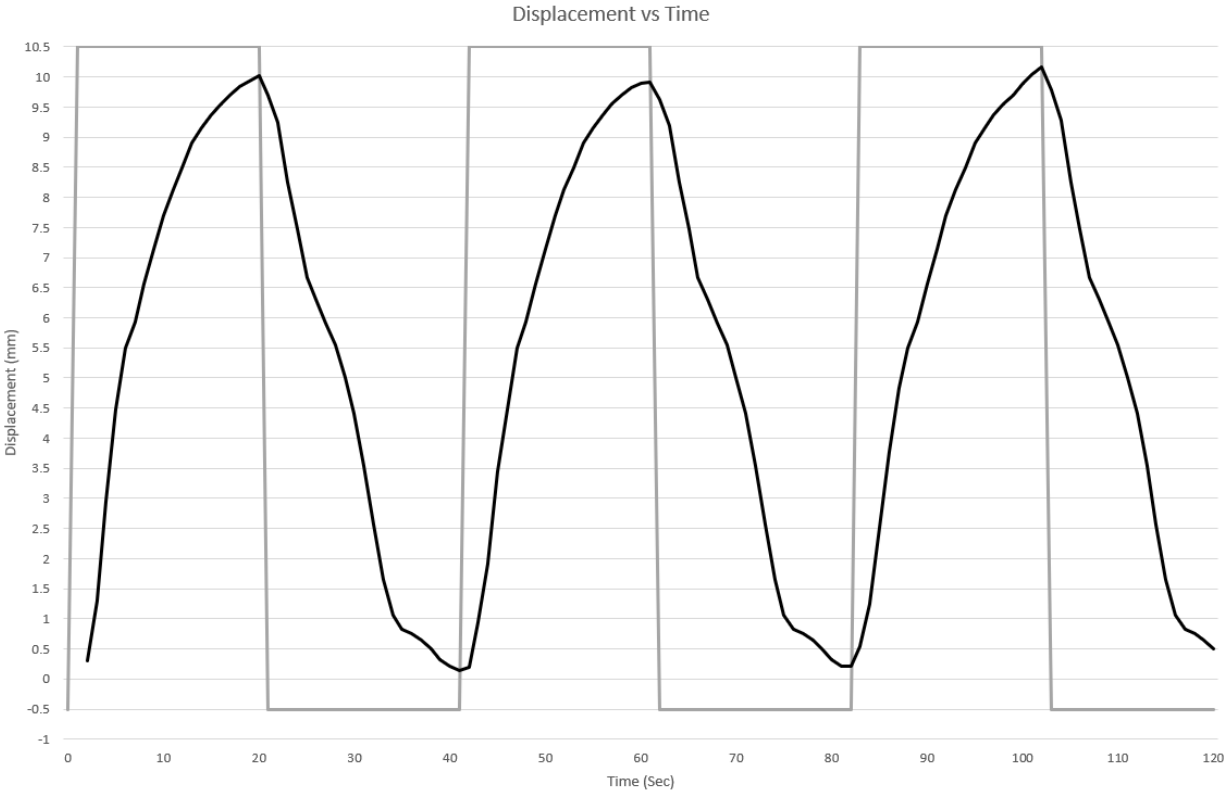

Figure 3.6: Displacement Versus Time Analysis of CNT Actuator

After analyzing the line graph developed from the displacement experiment, two conclusions were drawn. The first observed conclusion was the repeatability of the actuation. Each time the actuator was exposed to the light source, it would actuate repeatedly towards 10 mm ± 3 mm. Secondly, it was determined that the maximum displacement was observed at 10.164 mm.

3.3.2 Strain Analysis

The strain was calculated by utilizing the displacement and initial length of the actuator. Therefore, our team utilized a similar process to the displacement experiment with a minor modification. This time instead of a constant exposure, the light intensity was carefully increased by linearly varying the voltage being applied to the LED arrays from 0 mW cm^{-2} to 151.87 mW cm^{-2}. Similarly, the data was recorded and reported in a line graph presented below:

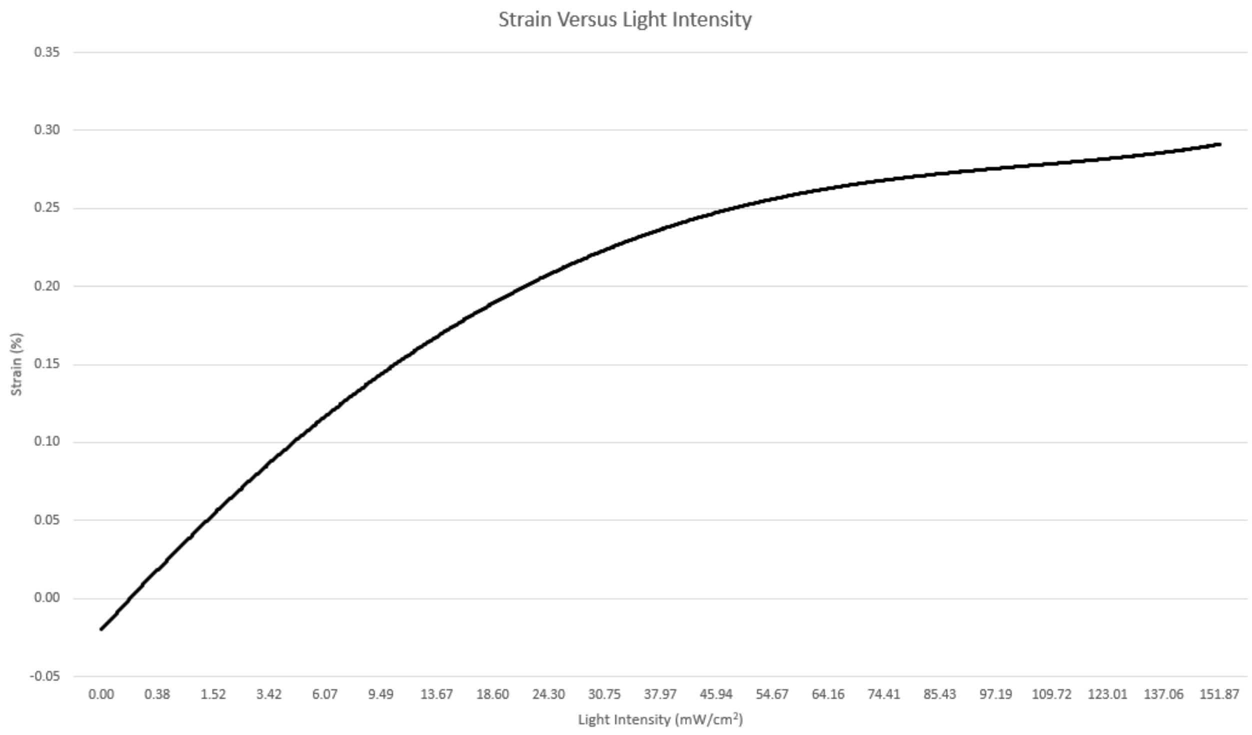

Figure 3.7: Strain Versus Light Intensity Analysis of CNT Actuator

At the conclusion of the experiment, the team was able to determine that the CNT actuator was able to undergo a significant amount of strain given the maximum light exposure. This strain without any load was calculated at 0.3%, which is significant given many photo-strictive and piezoelectric materials do not exceed 0.1% maximum strain (Lu, 2005). This data was used to determine the design of the light actuated robotic system later in the report.

3.3.3 Stress Analysis

The stress was calculated using the force applied by the cantilever CNT actuator divided by the cross-sectional area of the actuator. Accordingly, the dark box needed to be slightly altered to complete this experiment by incorporating a weight and a digital scale. During the experiment, the weight was rigidly attached to the non-clamped end of the CNT actuator and the weight was placed onto the scale which was directly below. The experiment was conducted by exposing the actuator to a light intensity of 151.87 mW cm^{-2}. The data and time were recorded by a LabView program and reported through an Excel spreadsheet. This spreadsheet was analyzed to observe plateaus of measurements signaling a lack of motion after the light has been exposed to the actuator given the weight. Once the data was cleaned up it was placed onto a line plot seen in the figure below:

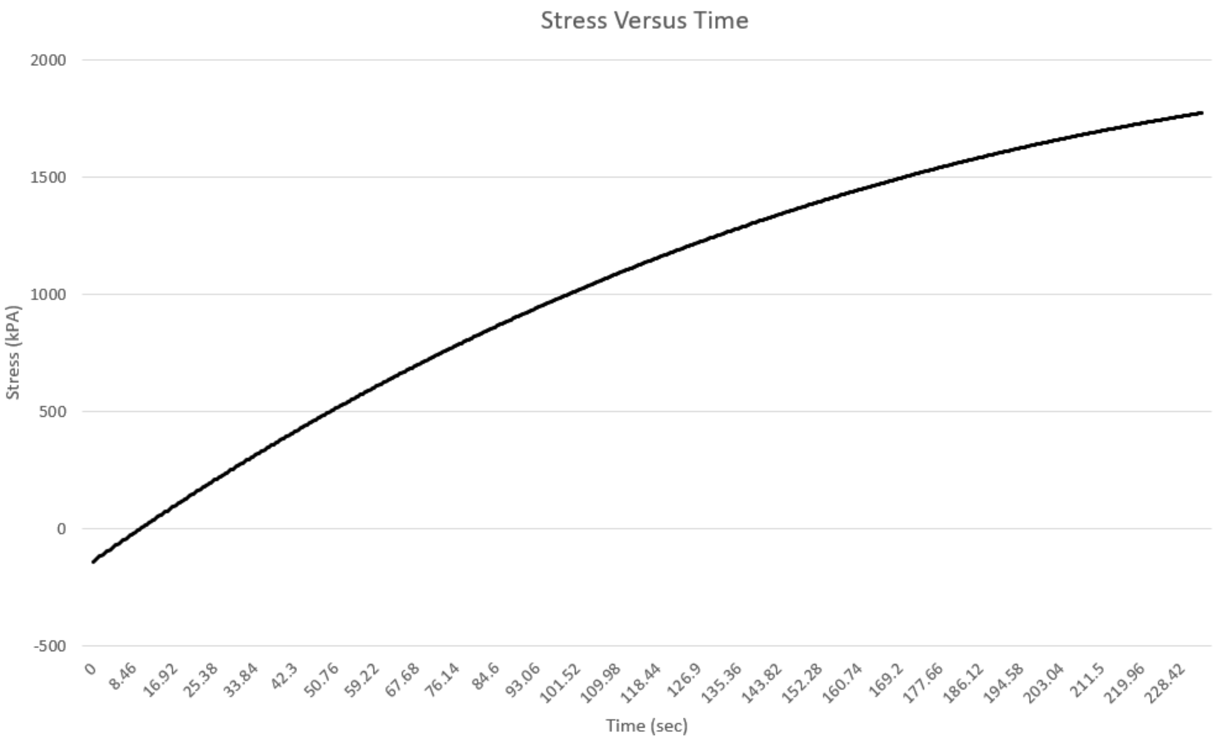

Figure 3.8: Stress Versus Time Analysis of CNT Actuator

There were two main conclusions observed throughout the experiment. The first main conclusion was the CNT actuator of size 1 cm by 4 cm is able to obtain a tensile stress of 1126.633 kPa given the 32.23-gram weight that was rigidly attached. The second conclusion was the increase in time for the actuator to move the attached weight. Typically, the actuator was able to complete a full actuation within 20 seconds once it was exposed to a light source; however, due to the increase in weight, the full actuation required 228.42 seconds. This conclusion was an important consideration for designing the structure of the robotic inchworm, as well as how long the actuation takes to complete.

3.3.4 Stress Versus Strain Analysis

The stress-strain curve presented a beneficial and graphical way to present the reaction of a material given a presence of a load to the team. For the scope of our project, our team decided to not observe the yield point of the material due to a lower required strain and stress of this research project. Based upon the recorded data in the previous experiments, we determined the curve was well within the elastic region. Furthermore, through research our team compared our results to existing data of CNTs being tested up to 110+ GPa before reaching a yield point with a similar strain (Wernik, 2010).

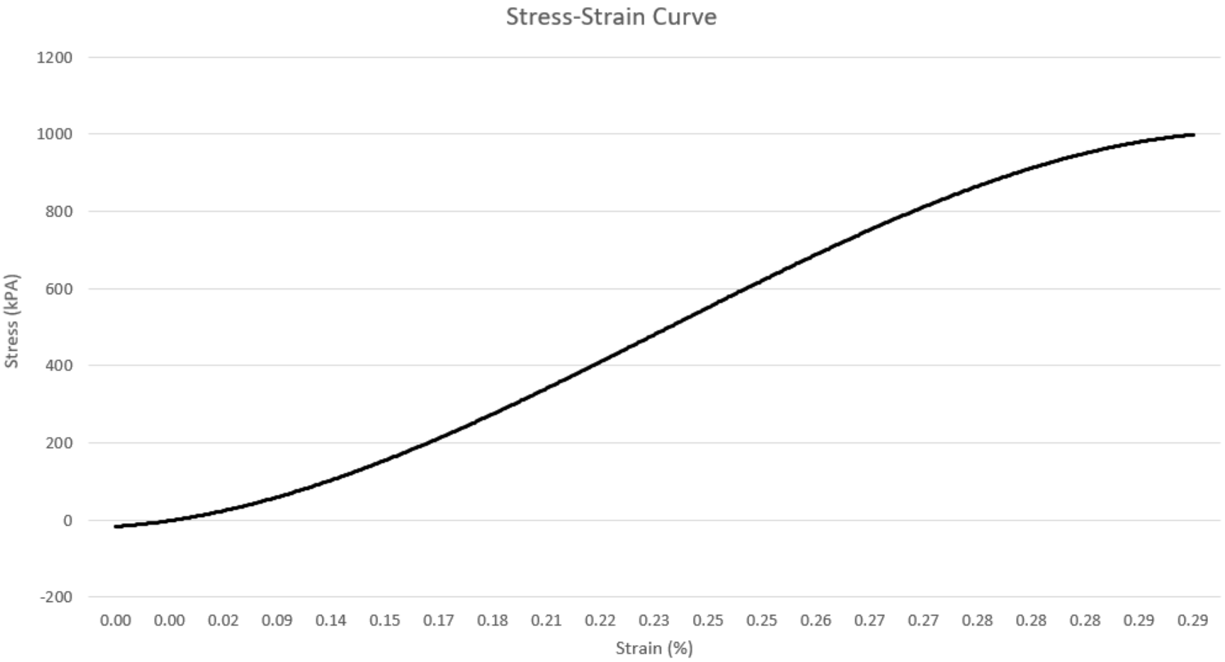

Figure 3.9: Stress Versus Strain Analysis of CNT Actuator

Chapter 4

Robotic Inchworm

Utilizing the manufactured cantilever CNT actuators, our team developed a proof of concept by demonstrating the ability to design and control a soft robotic inchworm developed from the CNT actuator given the presence and absence of light exposure within a controlled testing apparatus.

4.1 Methodology & Materials

4.1.1 Task Specifications

The second stage of this research MQP focused on developing a proof-of-concept soft robotic inchworm. This proof-of-concept was developed by our team to demonstrate control of the cantilever CNT actuators with a simple Arduino/MATLAB program. The goals of this stage for the research project are as follows:

- Develop a testing apparatus for the soft robotic inchworm
- Determine a transparent material to assist with the robot’s motion
- Determine ideal robotic inchworm feet configuration for motion
- Develop Arduino/MATLAB program for LED arrays
- Desired motion of three inches
- Calculate displacement and velocity of robot’s motion

Utilizing these goals, in the order presented, our team was able to develop a robotic inchworm that would prove and demonstrate the concept of controlling a CNT actuator by varying light exposure presented to the robot. Furthermore, the team deemed all the goals to be realistic and achievable within a timely manner allowing for plenty of time to complete the final stage of the project.

4.1.2 Work Schedule

Throughout the majority of B-term and beginning weeks of C-term, the team worked in parallel with streamlining the manufacturing process for the CNT actuators to develop the soft robotic inchworm. Therefore, these weeks were utilized by the team to develop the testing apparatus, Arduino/MATLAB program, and an ideal soft robotic inchworm through testing and experimentation.

4.2 Mechanical System

For the robotic inchworm, the team developed a basic design utilizing minimal materials. We developed this iteration to determine whether the CNT actuators can actuate promoting movement, while having the ability to be controllable. The following sections will describe the process the team underwent to determine the optimal final design for the robotic inchworm. The final design for the robotic inchworm can be found below in Figure 4.4.

4.2.1 Body Design

The body of the robotic inchworm is composed of a CNT actuator. The CNT actuator was made of a SWNT free-standing film attached to a PVC film via double-sided acrylic elastomer and then covered with a single-sided acrylic elastomer. The body of the robotic inchworm is pictured below in Figure 4.1:

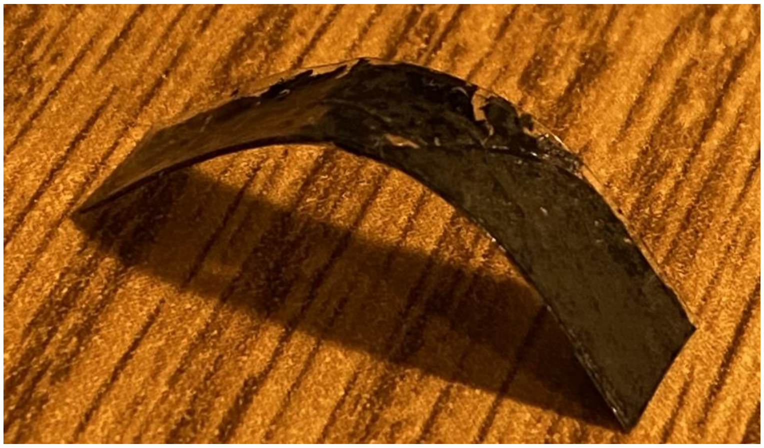

Figure 4.1 Robotic Inchworm’s Body

This straightforward design was selected to minimize the amount of force required to overcome the current state of inertia (e.g., a stationary state), thus allowing the team to promote actuation similar to Chapter 3's Results and Discussion section and demonstrate control of a soft robotic system.

4.2.2 Feet Design

We initially developed the feet of the robotic inchworm out of aluminum foil. Aluminum foil was chosen for the material because of its light weight and is easily molded into a desired shape. Utilizing the aluminum foil, the team developed and tested various feet configurations to determine the most effective design (Figure 4.2).

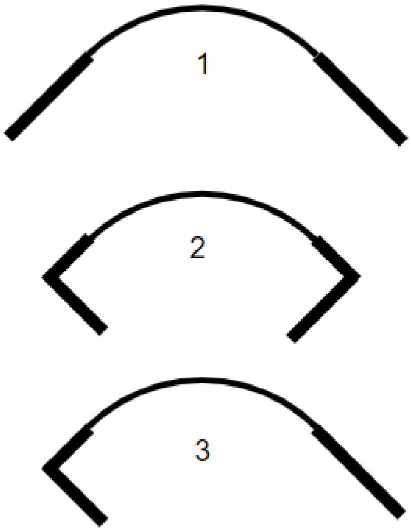

Figure 4.2 Robotic Inchworm Feet Designs

Each of the feet configuration underwent testing to determine which feet configuration promoted the greatest horizontal distance traveled. The aluminum foil feet were rigidly attached to the actuator shown in Figure 4.2 using heat tape. Next, the aluminum foil was molded to the various designs shown in Figure 4.2, respectively. After preparation was complete, we exposed the inchworm to three LED arrays and the horizontal displacement of the robotic inchworm was measured. Each of the feet configuration completed the experiment and data was recorded by the team. Based on the data found in Table 4.1, the team determined that feet configuration three was the most effective.

Configuration	Displacement (mm)
1	0
2	0
3	5.03

Table 4.1: Measurements from Feet Design Testing

After the team determined the ideal configuration for the robotic inchworm's feet, we decided to manufacture the feet. Our team developed the feet in a CAD and utilized 3D printing to develop a polished foot design for the robotic inchworm, seen in Figure 4.3.

Figure 4.3 Robotic Inchworm's 3D Printed Feet

The team attached the 3D printed feet to the robotic inchworm and conducted initial testing for walking the system. However, the team concluded after the initial testing that the 3D printed feet were too bulky for the desired application since they could not grip the protrusions along the surface of the testing apparatus discussed in subsequent sections. The protrusions were necessary because the inchworm would be unable walk on the smooth acrylic surface. The team chose to shift to a new material for the feet: tin. Small pieces of tin were synthetically shaped and rigidly attached to the inchworm. The tin feet allowed for the most horizontal movement out of the inchworm, therefore tin was chosen as the final material for the feet of the inchworm.

4.2.3 Final Mechanical System

After the team determined a body and feet design that promoted the greatest displacement, the final mechanical system for the robotic inchworm was constructed. Initially, we developed the robotic inchworm in a CAD software to observe the interaction and motion of an ideal robotic inchworm. Once the interaction of parts and motion was deemed suitable, our team constructed the final mechanical system seen in Figure 4.4.

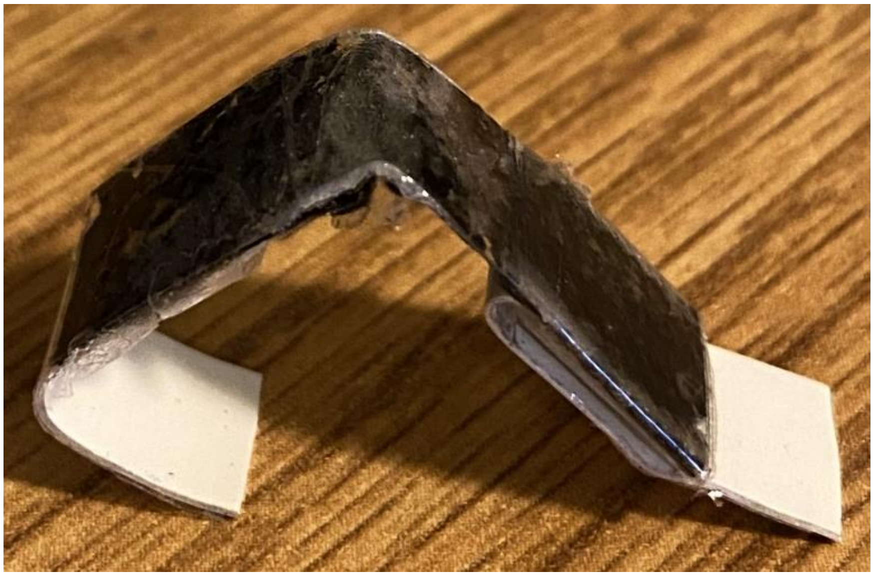

Figure 4.4: Robotic Inchworm's Final Mechanical System

4.3 Electronic Infrastructure

The purpose of the robotic inchworm was to demonstrate control of the soft robotic systems utilizing CNT actuators by regulating the motion. To control the robotic inchworm, our team decided to employee a basic open-loop control system. The reference input of the system is a high (5-volt digital signal) or low (ground signal) to the relay (controller). The controller the system converts the reference input to a 0-32-volt DC signal to power the LED arrays. The constant brightness from the LED arrays is summed with the brightness of the natural light (positive disturbance) and the summation of the two is used to illuminate the testing apparatus (plant) to the desired light intensity. This system can be seen in Figure 4.5 below:

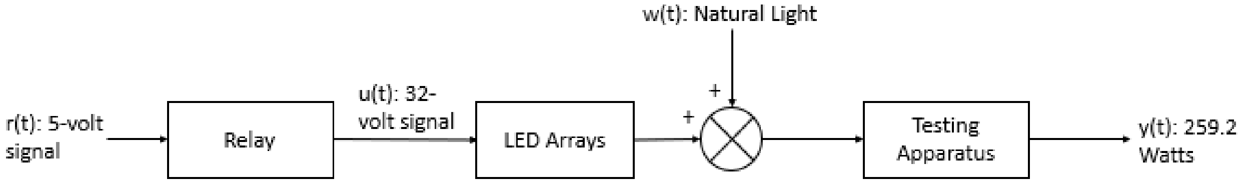

Figure 4.5: Block Diagram for Open-Loop Control System

After the control system was designed, the physical system was identified by the team. The Arduino is responsible for keeping track of the elapsed time and sending a high (5-volt digital signal) or low (ground signal) when the timer has expired the given interval. The relay is responsible for acquiring the high or low signal to active an electromagnet. The electromagnet actuates the switch depending on the signal to power on or off the LED arrays with an external 32-volt, 2.7 ampere power supply, in order to provide 259.2 Watts to the CNT actuator. The circuit diagram of the open-loop control system can be demonstrated in Figure 4.6.

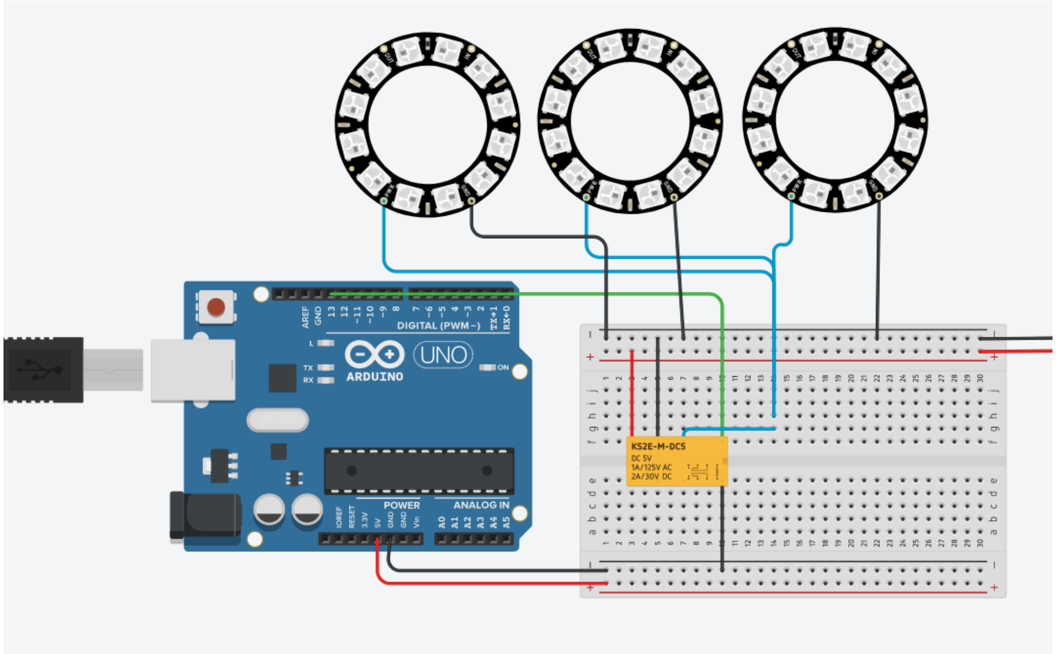

Figure 4.6: Circuit Schematic for Open-Loop Control System

4.4 Program Infrastructure

In reference to the physical electrical system, our team programmed the Arduino to send an alternating high and low signal after the time interval has elapsed. To control the input signal, a state diagram was derived to demonstrate the behavior of the system's input signal (Figure 4.7).

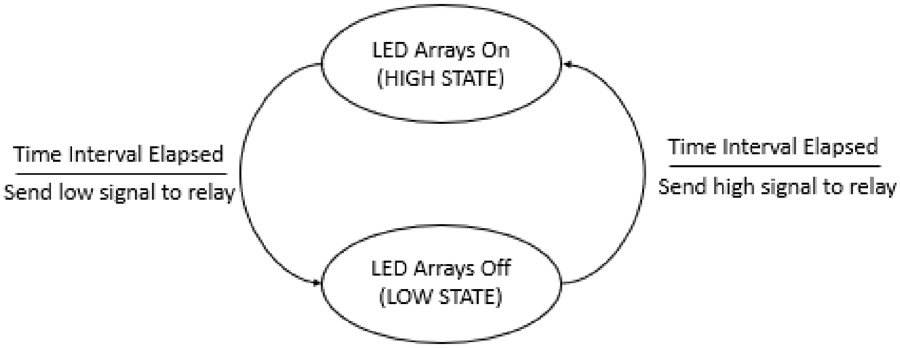

Figure 4.7: State Diagram for Control System Input Signal

The team determined that the previous state diagram was necessary to send a high and low signal to the relay for the open-loop control system. Therefore, the state diagram was broken down into two parts: a high state and a low state. Using these states, the team knew that the system took 20 seconds to fully actuate the CNT actuator. Therefore, a 20 second interval was utilized as a trigger. After the 20 second interval elapses, it triggers the Arduino to send the inverse signal to the relay, switching the state of the LED arrays.

4.5 Implementation & Testing

4.5.1 Testing Apparatus

To test the robotic inchworm, we developed a testing apparatus specifically designed for walking the robotic inchworm. The testing apparatus was composed of three LEDs, a piece of acrylic, and multiple VEX parts (Figure 4.8).

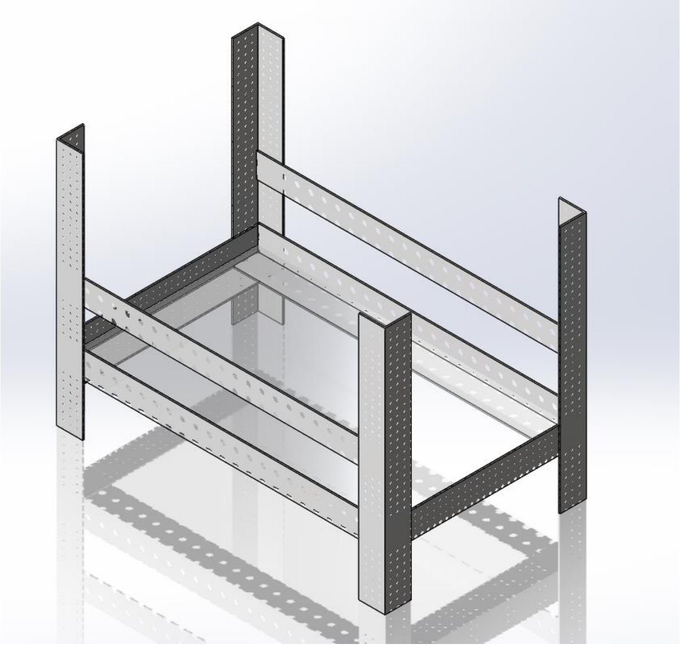

Figure 4.8: Testing Apparatus for Robotic Inchworm

4.5.1.1 LEDs

Three high-powered LEDs were utilized in the testing apparatus to promote actuation for the robotic inchworm. The three LEDs used were LOHAS 100W LED Chip Cool White Bulb High Power Energy Saving Lamp Chip. The LEDs dimensions were 1.97 x 1.97 x 0.08 inches and required 30 volts to power on. These LEDs assisted in process of testing the carbon nanotube actuators and the robotic inchworm. In the initial stages of the project, a flood light was utilized to test the actuation of the carbon nanotube actuators. However, the flood light produced over 60°C amount of heat that would warp the actuators due to the actuator's composition being made up of various plastic. With this negative effect, team chose the LEDs as the preferred form of light because of the heat being dispersed to the built-in heat sink.

4.5.1.2 Acrylic Base

A clear, ¼ inch thick acrylic with the dimensions 11 x 7.5 inches defined the task space that the robotic inchworm interacted within. The clear acrylic suspended the CNT actuators above the LEDs and allowed the light from the LEDs to interact with such actuators. Furthermore, masking tape was utilized in a ladder format to create the protrusions, mentioned in section 4.2.2, on the acrylic to assist the robotic inchworm's movement (Figure 4.9).

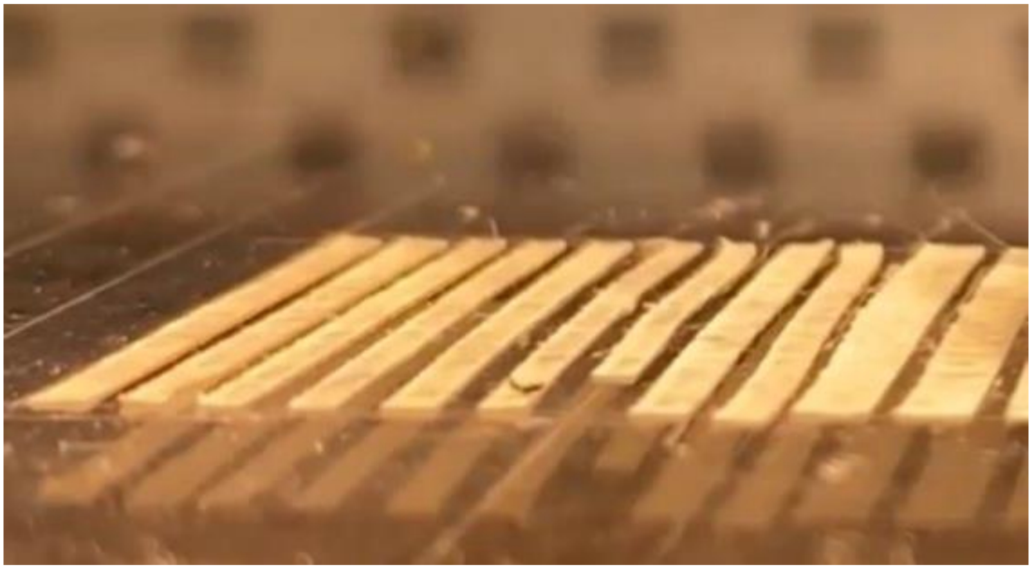

Figure 4.9: Ladder Pattern for Acrylic Surface

4.5.1.3 VEX Components

As mentioned above, VEX parts were utilized to construct the base of the testing apparatus. Four 10-inch L-channels defined the four corner towers. Two 12 ½-inch and two 7 ½-inch L-channels were utilized to create the base on which the acrylic piece will rest. Two 12-inch C-channels were employed to suspend the LEDs above the task space. The entire testing apparatus was held together with multiple nuts and bolts where appropriate.

4.5.2 Displacement & Velocity Measurements

4.5.2.1 Displacement Analysis

To observe the displacement of the robotic inchworm in a singular step, our team utilized the testing apparatus explained in Section 4.5.1, along with a metric ruler and the internal timer within the MATLAB program developed for this specific robotic system (Section 4.4). The testing apparatus was configured with the metric ruler rigidly attached to the rear L-channel (from a side view of the testing apparatus). A slow-motion camera was mounted colinearly to the metric rule for the observation of the total distance traveled in a singular step. Once the testing apparatus was fully configured for the experiment, the robotic inchworm was placed on the task space and the MATLAB program was ran a total of five times. This allowed our team to analyze each step and get an average distance covered by the actuator in a singular step. The results are presented and discussed in the “Displacement and Velocity Measurements” section of the report.

4.5.2.2 Velocity Analysis

The next analysis our team conducted to analyze the robotic inchworm was a velocity analysis. The displacement experiment allowed for parallel calculations of velocity using the pre-existing displacement information and the internal MATLAB timer. Using the basic velocity formula presented below, our team was able to calculate and present the velocity data after the completion of the displacement analysis. The results can be found in the “Results and Discussion” section of this chapter.

$$velocity = \frac{\Delta distance}{time}$$

4.5.2.3 Displacement & Velocity Study

The initial displacement and velocity analysis was a valid experiment for observing the motion of the robotic inchworm in a full actuation cycle; however, in order to demonstrate control, our team designed an experiment to show the robotic inchworm's ability to move a variety of displacement measurements depending on the duration of the light exposure. In this study, our team utilized the MATLAB program with a varying time interval for the LEDs to be on (5, 10, 15, and 20 seconds). Similar to sections 4.5.2.2 and 4.5.2.3, the team ran the test a total of five times consecutively with both displacement and velocity being calculated in parallel. The average of the displacement and velocity were taken and reported in section 4.6.2

4.6 Results & Discussion

4.6.1 Displacement & Velocity Measurements

At the conclusion of the analysis and study for the displacement and analysis, our team was able to derive two conclusions from the data recorded. The first conclusion that was determined by the team was rough linear displacement that was able to be achieved by the CNT actuator. Since the robotic inchworm required a specific material in order to propel itself forward, this was an expected result from the data as it required to overcome the protrusions from the smooth acrylic surface of the testing apparatus, as well as move over the rough masking tape lines. This can cause a slight discrepancy in the robotic inchworm's ability to displace itself to a new location. This phenomenon confirms the rough linear displacement observed in Table 4.2.

Our team was able to conclude that the velocity was constant with an average velocity of 0.2465 mm/sec and a variation of ± 0.0065 mm/sec (Table 4.2). Similar to the discussion above, this slight variation in velocity was due to robotic inchworm's ability to traverse the specialized terrain that our team developed in order to propel the inchworm forward and demonstrate basic control of the robotic inchworm.

Time Interval (Seconds)	**Displacement (mm)**	**Velocity (mm/sec)**
5	1.20	0.240
10	2.41	0.241
15	3.8	0.253
20	5.03	0.252

Table 4.2: Displacement and Velocity Table

Overall, the purpose of the analysis and study was to demonstrate the ability for a robotics engineer to control a soft robotic system utilizing CNTs. Since smart materials such as CNTs are a relatively new field, the project helps propel the research field forward demonstrating the ability to control and develop more complex robotic systems for any general case rather than one specific case such as a full actuation cycle of 20 seconds.

Chapter 5

Conclusions & Future Research

5.1 Future Research

5.1.1 Computer Vision

One source of error within the final robotic inchworm was the inability to control the system to a specific distance. We developed the ability to control the robotic system utilizing different light exposure durations. However, future teams could expand upon this control system to develop a closed-loop control system utilizing computer vision. The computer vision algorithm could incorporate MATLAB’s Image Processing Toolbox to detect the total displacement exhibited by the inchworm to control the state of the LEDs. With the development of a closed-loop control system, future teams could demonstrate the ability to control the robotic inchworm to significantly small displacements depending on the resolution of the camera.

5.1.2 Sensors

Sensors are an essential part to any robotic system because they allow the robot to see its environment. Specifically, distance sensing allows for a robot to complete obstacle avoidance. Without obstacle avoidance, the robotic system could potentially get stuck, fail to run its program, or even cause damage to the robotic platform. With the lack of time within the academic year, sensing on the robotic inchworm was omitted. Future teams could expand upon the teams work to develop a robotic inchworm that is ability to traverse a variety of different environments utilizing sensors such as lidar.

5.1.3 Future Applications

There are many applications in which CNT actuators could replace traditional actuators in a robotic system. Within this section, the team reported the potential of CNT actuators for space exploration, within the medical industry, and future MQP projects.

5.1.3.1 Space Exploration

Robotic systems employed by the space industry are launched into orbit with the assumption they will not get the parts back after the robot’s lifespan has passed. Once the battery’s radioactive lifespan passes after approximately 14 years, the robot is essentially forgotten. To combat this dilemma, future teams could construct hybrid robotic systems incorporating traditional actuators for the movement of the robotic base and CNT actuators to complete other tasks such as collecting samples. These hybrid systems could utilize an optical iris to concentrate light from the sun onto the CNT actuators, which would invoke a mechanical actuation. Utilizing this technology could increase the length of missions and life of any robotic system placed within space.

5.1.3.2 Medical Industry

One hinderance that is affecting the medical field is the inability to perform surgeries within advanced scanning technologies such as MRI machines. MRI machines take very detailed images of the human body, however, are severely impacted by the presence of metal. The CNT actuators, which can be used to develop non-magnetic systems, can be utilized by future teams to replace traditional motors within a robotic system to allow it to be utilized within an MRI machine. With the combination of CNT actuators and advanced scanning technologies, it is predicted that field of medicine and surgery could see substantial benefits with this future work.

5.1.3.3 Robotic Manipulator

There is still work to be done in demonstrating the ability to control multiple CNT actuators within a robotic system. Future MQP teams can expand upon the team’s procedures and results to develop a robotic manipulator that utilizes five CNT actuators for its fingers. To control this system, the team could employee the use of lasers focusing it directly onto each individual CNT actuator allowing them to displace about their rigid attachment point separately. By placing carbon nanotube actuators in a specific configuration, they could open and close like fingers based on the presence and absence of light. This is only one example of a potential expansion upon researchers’ ability to solve the control problems observed with these CNT actuators.

5.2 Conclusion

This project explored the relatively new research field of smart materials focusing primarily on CNTs, which laid the foundation for future developments of robotic systems utilizing the CNT actuators. Throughout the duration of this project, our team was able to meet the goals that defined the scope of the project. Over the course of the past academic year, the team developed a refined and optimal manufacturing process for obtaining free-standing SWNT films that produce CNT actuators capable of responding desirably to the presence and absence of a light source. Additionally, our unique research presented the mechanical characteristics associated to the synthetically constructed CNT actuators by determining the average displacement, strain, and stress exhibited in a controlled environment. The robotic inchworm developed by the team demonstrated the ability to control on any robotic system, which shows the unique ability to conform these actuators to any desired application. Our team hopes that industry professionals will be able to one day develop non-magnetic robotic mechanisms with the help of our work completed throughout this project.

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Appendices

Appendix A: Iteration 1 Experiment Procedures

1. Set the hot plate to 120 C
2. Pour 85 mL of deionized water in a beaker, and then add 15 mL of SDS (Sodium dodecyl sulfate)
3. Based on what we need (concentration of the CNT), we first calculate the desired concentration and then separate the amount of the CNT and add to the solution. (Here we need 1mg/100mL)
   And then place the solution in the sonicater for at least 20 minutes
4. Wash the silicon wafer with acetone, IPA, and DI water, respectively. Dry with N2.
5. Place the cleaned (washed) wafer on hot plate.
6. Prepare the filter holders and the disks.
7. Mount the funnel to filtration beaker in order to prepare the vacuum filtration.
8. We chose the 0.05 µm cellulose membrane and place it in the middle of the funnel.
9. After preparing and turning on the vacuum filtration, we add 100 mL of DI water to soak the membrane and then add the 100 mL solution to it.
10. Then we wait until it is completed and cannot see any droplets. (wait ten minutes after seeing the last droplet)
11. Then add 25 mL IPA to wash the previous SDS and then when it’s gone, add 300 mL of DI water and wait to see we do not have any droplets.
12. When it is finished, provide an Ethanol with dish and soak the membrane filter in it and then put the membrane on the (cleaned) wafer on the disk and then put a (circular) napkin on top of the membrane. And then hold the disk and press the whole disk for a couple of times.
13. Then put the whole disk on the 80 *C hot plate for 40 to 50 seconds and then remove from hot plate.
14. Now prepare the beaker with 400 mL of acetone in it and put a funnel on top and a cover on the hot plate and wait to see the bubbles.
15. Now we can open the disk and quickly put the wafer in the funnel and wait until to see the droplets of the membrane.
    When it is finished, wait ten minutes
16. Then rinse the wafer with acetone, IPA, and DI water and dry with N2.

Appendix B: Iteration 3 (Final Process) Experiment Procedures

1. Disperse 16mg of SWNTs into 100 mL of IPA.
2. Agitate the solution for 20 hours in a sonicater.
3. Mount the funnel to filtration beaker in order to prepare the vacuum filtration.
4. We chose the 0.22 µm hydrophobic PTFE membrane and place it in the middle of the funnel.
5. After preparing and turning on the vacuum filtration, we add 20 mL of DI water to soak the membrane and then add the 100 mL solution to it.
6. Then we wait until it is completed and cannot see any droplets.
7. Immediately remove the membrane and rinse twice in IPA and DI water.
8. Place membrane flat in petri dish for 2 hours.
9. Remove SWNT film from membrane with utility knife
10. Dry SWNT film for at least 22 hours after removal.