DESIGN OF SOFT ROBOT FOR MANEUVERING IN TIGHT SPACES

Tan Zitang

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Mechatronics Engineering with Honours

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

September 2023

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature	:	
Name	:	Tan Zitang
ID No.	:	1900544
Date	:	10/08/2023

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DESIGN OF SOFT ROBOT FOR MANEUVERING IN TIGHT SPACES"** was prepared by **Tan Zitang** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Mechatronics Engineering with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature :

Supervisor : Dr Low Jen Hahn

Date : 15/9/2023

Signature : Chee Pei Song

Co-Supervisor : Dr Chee Pei Song

Date : 17/9/2023

ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Dr. Low Jen Hahn for his invaluable advice, guidance and his enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving parents and friends who had helped and given me encouragement to complete my final year project. I would like to thank my co-supervisor Dr. Chee Pei Song for giving me advices about the structure and design. Besides, I specially thank Dr. Low Jen Hahn for giving me guidance and assisting me on fabrication of the soft robot’s body. Last but not least, my sincere thanks to Dr. Shalini for giving me advice on the pneumatic system circuit connection.

ABSTRACT

Soft robotics is an emerging field that combines engineering and materials science. Soft robots, as compared to typical rigid robots, are built with flexible and pliable materials, allowing them to adapt to complex and dynamic surroundings. It provides unique answers to difficulties that traditional robotics cannot handle by imitating the softness and adaptability of natural organisms. This project demonstrates the fundamental principles, design strategies and the application of soft robot, such areas include healthcare, exploration and also human-robot interaction.

This project narrows down and focuses on the design of soft robot for maneuvering in tight spaces. Pneumatic actuation and pleated segment structure is chosen to design the soft robot. Where the material chosen was Ecoflex. All of these considerations were made because they are easy to use and applicable to build a simple maneuverable soft robot. Finite Element Modelling was performed to compare different types of soft robot structures having different bending motion as three different types of structures built to obtain the optimal design for the soft robot.

In the end of the experiment, it can be observed that higher frequency applied to the solenoid valves will lead to higher voltage that able to apply to the micro pumps and causing the distance travelled by soft robot to be further in 60 seconds. Among the 3 types of different design of soft robot, the fully covered type is found to be more stable and not break easily. Whereas the unfully covered with thicker wall, which is the best design in this project travels further and forms a better bending shape.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The field of soft robotics has recently experienced one of the most rapid expansions, and its academic emergence suggests that it has the potential to alter the place of robots in both society and industry (Cianchetti et al., 2015). The scientific field is still developing due to having great potential. A review of claims that the term “soft robot” was originally applied to a rigid pneumatic hand with some object compliance because of gas compressibility (Tondu and Lopez, 2000). After that, the phrase “soft robot” appeared in a few of reports and papers, but it continued to refer to a robot and other device made of rigid materials. In 2008, the term “soft robotics” was first used to describe the study of stiff robots with flexible joints, which is soft material-based robots with large scale of mobility, flexibility, and the ability to adapt (Albu-Schaffer et al., 2004, Laschi et al., 2014).

Efforts to construct new robots that are fundamentally different from their classic rigid counterparts began even before professional terminology was developed. In the 1950s, McKibben developed braided pneumatic actuators for an orthotic device for paralytic patients. McKibben’s artificial muscle was thoroughly explored and utilized in a variety of robot designs (Krishna et al., 2011). In 1990, Shimachi and Matumoto reported their research on soft fingers. Suzumori and his colleagues proposed their flexible microactuator made of silicone rubber a year later and tested it in many different kinds of applications (Wakimoto et al., 2009, Suzumori et al., 1992). Over the decade that followed, similar devices such as pneumatic bellows actuators, pneumatic rotary soft actuator, fluidic muscle, flexible fluidic actuator, Clobot, caterpillar robot, and continuum manipulators were developed (Boblan et al., 2004, Camarillo et al., 2008, Chen et al., 2009, Guanjun et al., 2017, Kornbluh et al., 1998, Noritsugu et al., 2001, Robinson and Davies, 1998, Schulz et al., 2001, Trimmer et al., 2006). These actuators and sensors, despite having different mechanisms, designs, and motion performance, are definitely significant advancements in the field of soft robotics (Cianchetti et al., 2015, Wang et al., 2015).

Soft robotics have been existed around for about 50 years, but only recently has it become more well-known among researchers and the public. As these technologies gain acceptance in the robotics community, an increasing number of scientists and engineers desire to contribute to the field. This is demonstrated by the growing number of laboratories, expanding publications, soft robot-related clubs and organisations, and special sessions at various international conferences, professional events, and activities. Although the field of soft robotics is still in its early stages, a few review articles have been published to highlight the achievements, assess methodology, and discuss concerns and prospects. These assessments were organized based on the technical content they included, but humans intended to provide an alternate perspective by using bibliometric analysis to present the historical chronology and overall image of the soft robotics research community.

1.2 Importance of the Study

Soft robots are high versatility as they are different from traditional rigid robots which soft robots have higher flexibility to adapt to different settings and carry out activities that would be challenging for their hard-bodied counterparts. Due to the characteristics of soft robots which they are soft and pliable nature, soft robots are safer than traditional robots as they are less likely to cause harm and injuries to humans and other living things. Although some of the other robots have high flexibility for certain application, among all of the robots, soft robots tend to have the highest flexibility. It can be programmed easily to perform many types of tasks, which is from simple movements to more complex behaviors. In medical field, soft robots play an important role and they had made a huge contribution in surgery operations based on its characteristics and behavior. Overall, the study of soft robots is important in advanced robotics technology and other fields including manufacturing and exploration.

1.3 Problem Statement

Traditional robots often have hard, stiff components, which restricts their ability to interact with their surroundings in a secure and useful way. They lack of the adaptability and flexibility needed to function in unpredictable and dynamic environments since they are built to carry out specified functions in a controlled environment. Because of this, they are less suited to jobs that require handling delicate items, dealing with people, or conquering difficult terrain.

There are several challenges found for developing soft robots. The primary challenge is developing innovative locomotion mechanisms that soft robot requires to move easily such as crawling or rolling. But due to the complexity of the shape of soft robot and the precise control that soft robot needed, it will be a big challenge during the design process.

Besides, soft robots might face speed restrictions as they are not able to perform in very high speed like the normal robots. This is caused by their possibility of deformation or unpredictable movement due to the fragile materials they are made of.

1.4 Aim and Objectives

This project is aimed to develop a soft robot that can operate on confined spaces. The objectives for the project are shown below:

1. To simulate the actuating mechanism of the soft robot.
2. To design a soft robot which can perform linear locomotion.
3. To apply soft robot under confined spaces.

1.5 Scope and Limitation of the Study

The direction of this study is to focus on designation of soft robot so that it can be implemented under confined spaces for certain purposes. The actuation mechanism, soft robot structure design and circuit control are the main focusing research of the soft robot designation in this study. However, there are some limitations that will be affecting the outcome for the research.

As mentioned, soft robots have different movement and they can carry out advanced activities compared to normal traditional robots due to their high flexibility properties. This might limit the research direction due to higher time consumption in doing trial and error experiments for getting the most perfect locomotion result to be implemented.

Besides, due to the current knowledge in circuit theory and lack of expertise resources from journal paper, this will be a big limitation in designing and implementing complex soft robot systems. The circuit system of designing the soft robot is needed to be highly concern so that the accurate frequencies of its locomotion can be obtinaed.

Next, the purpose of designing soft robot in this study is to apply soft robot in tight spaces. So, due to this reason, the soft robot must be designed in a smaller size and it cannot be built to carry higher loads. This may lead to material limitations in the reaseach as it is very difficult to find micro electronic parts that control the movement of soft robot.

1.6 Contribution of the Study

Soft robotics research frequently seeks to discover fresh materials, design ideas, or control algorithms that can improve the capabilities of soft robots. The contribution could include the development of new technologies that improve the performance, adaptability, or safety of soft robots.

Soft robots are ideal for exploring difficult and unstructured situations, such as disaster zones or undersea research. Research can help by developing robots that can better respond to environmental disasters or perform important activities in confined spaces.

1.7 Outline of the Report

This report is subdivided into five chapters, generally:

1. Chapter 1

   The first chapter is basically the introduction of the project, which consist of the general introduction of the whole project, importance of study, problem statement, aim and objectives of the project, the scope and limitations of the study and also the contribution of the study.

2. Chapter 2

   This chapter will describe all of the important considerations and concerns for designation of soft robot. The optimal material, actuation and structure to be implemented during building of soft robot as well.

3. Chapter 3

   For this chapter, it is about the discussion of experiment, fabrication procedures and any equipment to be utilized in this project. Besides, explanation of structures and electronic devices are included in this chapter.

4. Chapter 4

   Results obtained during experiment and also the best voltages to be applied on micro pump to get the furthest distance the soft robot can travel. The recommended structure of soft robot will be discussed in this chapter.

5. Chapter 5

   The last chapter will give the conclusion to the whole project. Problem encountered in this project and recommendations to overcome it will be stated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Soft robots are rapidly growing field that often inspired from biological systems which consists of soft materials, and they are being actuated by different types of actuators. They involve in designation, fabrication, controlling of soft robots using controllers, actuators and some different types of soft and flexible materials. The main task for soft robots is to operates difficult and mostly impossible tasks that are incapable for traditional rigid robots. For instance, manipulating delicate items and adapt to unstructured situations. Overall, soft robots are widely used in a huge variety of field like healthcare, manufacturing, researching, and rescuing missions.

2.2 Designation

Soft robots are flexible and can be operating in different kind of impossible tasks comparing with traditional rigid robots, designation of soft robots is mostly soft and flexible and can be deform under certain conditions. Basically, the body of the soft robots are made of some flexible materials like silicone elastomers, polymers or hydrogels. Besides, the most important part of soft robot is the actuator, which is to control the movement of the soft robot. Most of the actuators include hydraulic type, pneumatic type or shape-memory alloys (SMAs). Other than that, a control system helps the soft robot to manage its movement and responses. The common control system used in a soft robot is the computer-based control system or some simple feedback loop system.

2.3 Materials

The materials chosen for designing soft robots must be concern as to meet the requirement of soft and flexible and to prevent conditions of materials being affect by external factors. There are certain types of basic and reliable materials could be utilized for soft robots’ production.

2.3.1 Silicone elastomer

Silicone elastomer is a type of flexible and stretchable material made from silicone and other molecules such as carbon, hydrogen and oxygen. It is durable and highly-resistant to chemical and temperature (which can withstand temperatures approximately ranging from $-50°C$ to $350°C$). The structure of silicone elastomer contains siloxane backbone and organic moiety which bounded to the silicone like Figure 2.1.

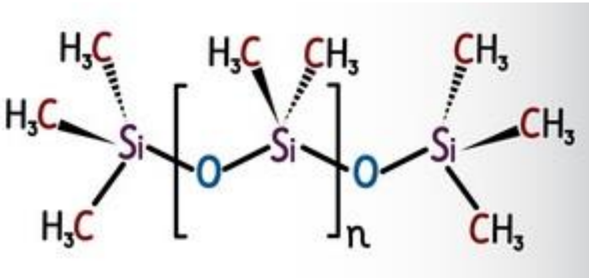

Figure 2.1: Chemical structure of a Silicone elastomer (Omnexus).

2.3.1.1 Polydimethylsiloxane (PDMS)

Polydimethylsiloxane (PDMS) is grouped in the silicone elastomer family. It is mostly used in microfluidic applications to form micro-devices due to its remarkable properties such as flexibility, lower cost and ease of use. It can be implemented in designing soft robots due to its elasticity but the drawback of PDMS is that its mechanical properties are slightly low. To overcome this issue, pure PDMS can be mixed with other polymers or by adding particles to enhance its strength (Ariati et al., 2021).

2.3.1.2 Ecoflex

Ecoflex is one of the most popular silicone elastomers for fabricating purpose. It is manufactured by Smooth-On, Inc. It is intended for mold-making, casting purposes, and other artistic and industrial applications including soft robots' development. Ecoflex are mixed 1A:1B by weight and being cured under room temperature. Due to its softness and stretchiness, it is considered as a very good material for soft robots' fabrication.

2.3.2 Hydrogel

Hydrogels are mainly built in a network structure with water and hydrophilic polymer chains (Lee et al., 2018, Yang and Suo, 2018, Yuk et al., 2019). The configuration of the polymer network can be varied, and its strain can withstand up to 1000% (Sun et al., 2012). Hydrogels have a large volume fraction of water causing it to have an elastic modulus of 1-100 kPa range. It is applicable in the field of soft robots. The ions that dissolved in water will cause hydrogel to have a conductivity of 10 S/m. Figure 2.2 shows clearly about the chemical structure of hydrogel.

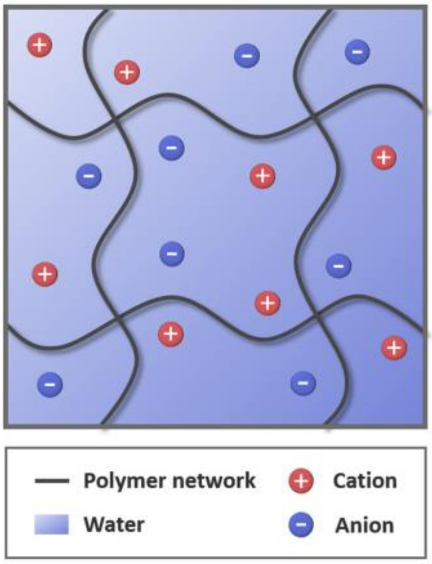

Figure 2.2: Chemical structure of hydrogel.

2.4 Types of Actuations

Actuation is a process which actuators convert electrical energy into mechanical force. Actuators are component that enables the movement of a whole machine. Both soft robot and traditional rigid robot requires actuator to perform certain movement. There will be some specific types of actuations that can easily controls the movement of soft robot, including pneumatic actuation, hydraulic actuation, shape memory alloys (SMAs) actuation and the electroactive polymers (EAPs) actuation. Besides, there is one rarely used actuation system because of its expensive cost, which is the hydrogel-based actuation.

2.4.1 Pneumatic actuation

Pneumatic driven soft robots will distribute into two pressure drives which is the positive and negative drives. The positive pressure driving technique is to fill the cavity inside the soft robot's body with compressed air for moving and deformation purpose. While the negative pressure driving technique is to draw out the air from the cavity which contained compressed air by vacuuming, and this will make the cavity to shrink so do the soft robot can go through moving and deforming process (Jihong et al., 2018). The actuator structure for pneumatic network is shown as Figure 2.3. From the Figure below shows that the actuator structure can be distributed into two layers which is the upper layer (extendable layer), and the lower layer (restricted layer). As the upper layer is consist of a linear aligned air chambers and they are interconnected by an air channel, the inner walls of the air cavities will expand and squeeze with each of them during inflation. In this moment, the bottom layer will restrict the body for lengthening. These actions produce a bending motion of the whole driver towards the restricted layer.

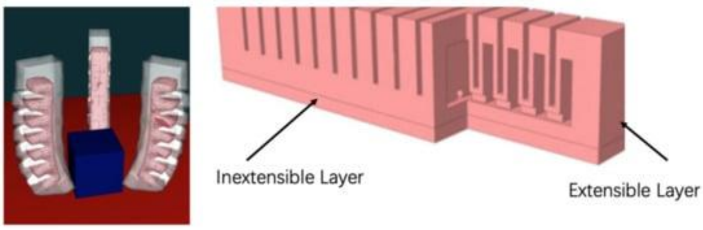

Figure 2.3: Pneumatic network structure.

2.4.2 Hydraulic actuation

Hydraulic actuation is a process of transforming hydraulic power into mechanical power, which is mainly referring the Pascal's law. This process allows the hydraulic actuators to exert a very huge number of forces in high speed. Basically, hydraulic actuation used mineral oil as their common fluids as it is very slightly compressible, making the actuation process to be fast. Besides, mineral oil which have the function of lubrication and cooling effect for the valves and pipes. Another commonly used fluid in hydraulic actuation is the water. The advantage for using water is that it is clean and safe to use but the limitation is that it has low water viscosity and will causes higher internal leakage. Hydraulic pumps are used to actuate the body of the soft robots' cavities. It will create a pressure gradient between two water reservoirs within the body. Figure 2.4 clearly shows the process of actuation on the soft robot's body.

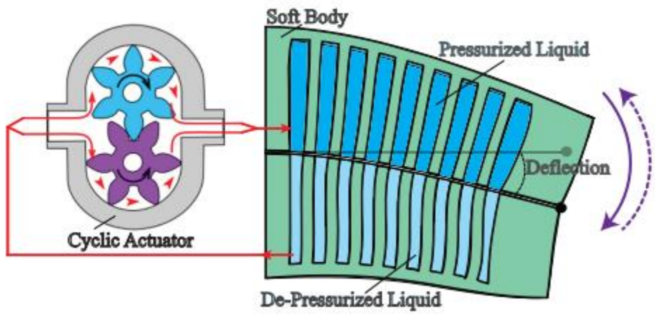

Figure 2.4: Cyclic hydraulic actuation of a soft body through an actuator which produce undulating motions (Katzschmann et al., 2016).

2.4.3 Shape memory alloys (SMAs) actuation

Shape memory alloys (SMAs) are material that will deform correspond to temperature changes. This actuation consists of two components which are the liquid metal capacitive and curvature sensor and the SMA actuator. It needs electrical to be powered for actuation process. Shape memory alloy like the nickel-titanium (nitinol) is commonly used as it has high working density, versatile on forming factor and able to be activated electrically through miniaturized, on-board power and electronics (Jani et al., 2014, Rodrigue et al., 2017). While mostly the liquid metal alloy used will be eutectic gallium-indium (EGaIn) due to its high electrical conductivity and low viscosity (Jeong et al., 2012, Jeong et al., 2015, Wissman et al., 2013). The linear motion of the SMA actuation is based on when current flow through the SMA heat will be generated, the atoms inside the wires will realign to another crystalline structure when heat past a transition temperature. A wire contract during heated and extend during cooled process is formed regarding this actuation result (Eitel, 2018).

2.4.4 Electroactive polymers (EAPs) actuation

EAPs change the mechanical and optical characteristics by applying an electrical field. It is widely used in soft robots' field because of its good actuation strains and high energy characteristics (Olvera and Monaghan, 2021, Rodrigues and Mota, 2016). There will be two groups for EAPs which is the dielectric EAP and the ionic EAP (Ariano et al., 2015, Li et al., 2021, Ohm et al., 2010, Salleo, 2007, Sappati and Bhadra, 2018, Shaikh et al., 2021). Dielectric EAP consist of dielectric elastomers, ferroelectric polymers, electrostrictive graft elastomers and liquid crystal elastomers. While for ionic EAP, there will be the ionic polymeric gels, conductive polymers and the ionic polymer-metal composites (Bar-Cohen, 2001). As summary, the electric field that is generated on the surface of electroactive polymers is what drives them most. The differences between dielectric EAPs and ionic EAPs is that dielectric EAPs are powered by accumulation and interaction of opposing electric charges on the surface of the elastomers during the stimulation of an electric field while the ionic EAPs were powered by movement or diffusion of ions.

2.4.5 Hydrogel-based actuation

Hydrogel based actuator can be differentiated into 6 different actuators based on the input stimuli. Thermally responsive actuator which mainly based on the changes of ambient temperature causing a volumetric change of hydrogels and produce deformation (Gao et al., 2017, Hu et al., 1995, Kim et al., 2015, Lu et al., 2010, Ongaro et al., 2017, Zheng et al., 2018). Secondly, the chemically responsive actuator is based on the chemical stimuli and causing the changes of hydrogel. The hydrogel forms a mechanical motion by converting chemical potential of the surrounding environment (Dong et al., 2006). Next, the optically responsive actuator will change the shapes or volume of the hydrogel by responding to the light irradiation. The advantage for this actuator is that it does not need any physical connection for energy transfer. Other than that, electrically responsive actuator, by referring with its name, which is changes of hydrogels' volume and shape based on electric stimuli (Keplinger et al., 2013). They react quickly and accurately using computational circuits. Next, the magnetically responsive actuator, which mainly changes the volume of hydrogel by responding to external magnetic field. Finally, the hydraulically responsive actuator, which cause hydrogel to undergo deformation by responding to the hydraulic pressure (Yuk et al., 2017).

2.5 Structure

As mentioned, the body of soft robots are not the same as the traditional robots as they are soft and flexible. The static, dynamic and kinematic models for soft robots are different comparing with the traditional rigid robots as to make them able to bend and deform and they have many passive degrees of freedom.

2.5.1 Ribbed segment

The ribbed segment is made of three layers. From the Figure 2.5 shows that during A, the segment is unactuated. During B, the segment is actuated where the channel group is pressurized. The segment is differentiated into few groups like the (a) soft elastomer, (b) embedded fluidic channels, (c) inextensible but flexible constraint, (d) embedded fluid transmission lines and (e) the ribbed structures (Marchese et al., 2014).

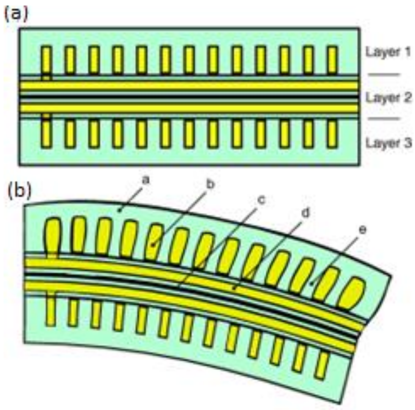

Figure 2.5: Concept of ribbed segment. (a) Shows before the air chambers being pressurized. (b) Shows after the air chambers being pressurized.

2.5.2 Cylindrical segment

The cylindrical segment relates to two fluid filled channels connected and located at the outermost layer like Figure 2.6. When one of the channels pressurized, the embedded channel will be bend in curvature and extended. The inner layer shows in Figure 2.6 is a stiff rubber that work as inextensible constraint. This segment is divided into 6 groups, which are the (a) crush-resistant silicone inlets, (b) soft silicone rubber outer layer, (c) expanding embedded fluidic channels, (d) stiffer silicone inner layer, (e) soft endplates and the (f) internal tubing bundle (Martinez et al., 2013).

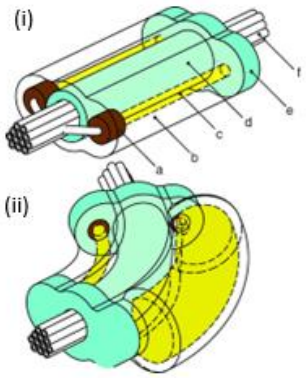

Figure 2.6: Concept of cylindrical segment. (i) Shows before the channels being pressurized. (ii) Shows after the channels being pressurized.

2.5.3 Pleated segment

Pleated segment structure is the most common seen structure in soft robotics field. It consists of an equally divided and discrete sections which separated by gaps. From the Figure 2.7 shows that, the hollow channels are connect with a center channel and reachable through a front inlet. During pressurization, one of the pleats will go through balloon-like expansion of the thin exterior skin. Overall, all the pleats added together and go through the balloon-like expanding motions will lead to the bending of soft robots. The pleated segment design distributed into 4 groups, which are the (a) channel inlet, (b) inextensible constraint layer, (c) even divided gaps and the (d) equal pleats (Martinez et al., 2013).

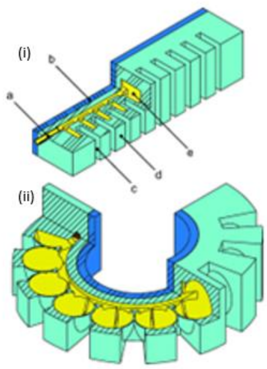

Figure 2.7: Concept of pleated segment. (i) Shows the cross-sectional area of the hollow channels before being pressurized. (ii) Shows the cross-sectional area of hollow channels after being pressurized.

2.6 Control and Electronics

There will be different kind of controllers that are able to control the whole system of the soft robots. Basically, they are the microcontrollers like Arduino, Raspberry Pi or ESP32 which have Wi-Fi and dual mode Bluetooth.

2.6.1 Arduino

Arduino is a platform that is open source uses user-friendly hardware and software. It consists of different kind of microcontroller boards like Figure 2.8 that allows users to upload code into it and let them microcontroller to operate certain tasks like control the connected output. There are several types of Arduino boards which have different specifications and capabilities, which are the Arduino UNO (R3), Arduino Nano, Arduino Micro and more. All these Arduino boards utilize Arduino programming language which is based on wiring and the Arduino Software (IDE) which is based on processing.

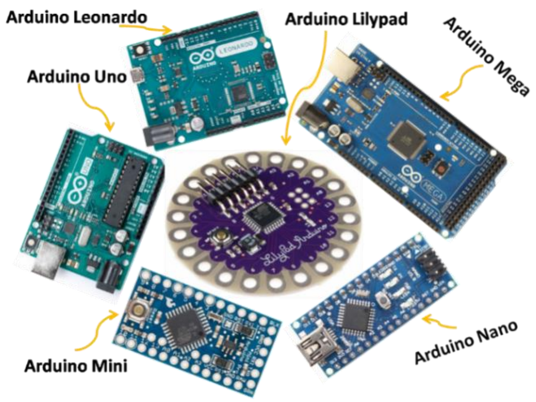

Figure 2.8: Arduino boards.

2.6.2 ESP32

ESP32 is a low-power system-on-a-chip (Soc) microcontroller and it is widely used in the Internet of Things (IoT) applications. It can perform as a system itself or as a slave device controller by microcontroller (MCU). ESP32 consists of Wi-Fi and Bluetooth function through its SPI / SDIO or I2C / UART interfaces, which allows it to connect with other systems. Figure 2.9 shows the model of ESP32.

Figure 2.9: ESP32.

2.7 Fabrication

Fabrication process is the final step for building a whole soft robot. Fabrication process of the soft robots can change according to the design and materials used. Theere are several types of fabrication techniques for building soft robots, like the 3D printing technique, mold casting and soft lithography.

2.7.1 3D printing

3D printing, also known as additive manufacturing (AM) is a process of fabricating three-dimensional physical object from CAD model or digital model. The process is bonding the material such as thermoplastic or resin layer by layer to obtain desired object. Fused deposition modelling (FDM) is one of the most popular material extrusion 3D printing processes. This process is to melt the thermoplastic filament and extrude through a nozzle to the printing platform and form a physical object (Turner et al., 2014). Besides, Stereolithography (SLA) 3D printing, also known as resin 3D printing process, is also considered as one of the popular 3D printing techniques. Comparing with FDM 3D printing, SLA 3D printing will be faster, and it has higher accuracy. This technique is based on localizing the photopolymerization within the printing vat filled with resin that is able to be cured in layer by layer way when it exposed to UV radiation (Shukrun et al., 2018). By using these 3D printing techniques, the body of the soft robot can directly be printed.

2.7.2 Mold casting

Mold casting fabrication is process to pour uncured liquid material like any silicone elastomer into a mold with specific shape and structure, where the mold can be 3D printed. Then the material will be cured into certain shape and the desired object will be formed. The body of soft robot can be produced by using this technique as the fabrication steps are not complicated. There is another technique which utilized mold to go through the fabrication process, which is the soft lithography process. Soft lithography is a technique that use elastomeric stamps or mold, which basically made of Polydimethylsiloxane (PDMS) to fabricate of replicating a structure. Figure 2.10 shows the two types of soft lithography. Microcontact printing is referring to the soft lithography method where the stamp is brought to contact with the substrates during the ink transfer. While Microfluidic patterning, which also referring to the soft lithography method used elastomeric stamp to create channels to let the ink to fill up (Sahin et al., 2018).

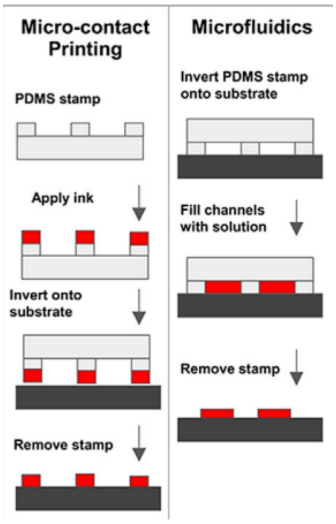

Figure 2.10: Soft lithography process (Sahin et al., 2018).

2.8 Summary

In summary, the soft robots will be designed into a flexible and easy to deform structure, which either the ribbed segment type, cylindrical segment type or pleated segment type. The materials that are applicable in building a soft robots include Silicone elastomer and hydrogel. These materials are certainly suitable as they can deform and flex easily. There are different types of actuations that are used commonly in designing soft robot, which are the pneumatic actuation, hydraulic actuation, shape memory alloys (SMA) actuation, electroactive polymers (EAPs) actuation and the hydrogel-based actuation. Control and electronics are important in any types of robots. For this case, Arduino and ESP32 can control the motion and actuation of the soft robot. Lastly, For the fabrication process, which is the last step of building a soft robot, 3D printing technique and mold casting are considered. These techniques are commonly utilized in fabricating the body of the soft robot.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter states the components, materials, and methods applied in the project. The actuation applied to the soft robot is discussed. The preparation and fabrication process and structure designing are included in this chapter. Then, the assembly of the soft robot body and actuator is explained.

3.2 Materials

Materials used for building the body of soft robot can be differentiated into few types. In this project, Ecoflex is chosen for building the body of the soft robot. The reason for using Ecoflex is that it is very flexible which achieved the requirement of building the body of soft robot and it has more simple fabrication comparing to other materials. Other than that, Ecoflex is good at tear resistant, which can withstand the pressure applied during pressurization and it will not dry up easily when going through fabrication process. Figure 3.1 shows the Part A and Part B of Ecoflex which will be mixed together in 1:1 ratio during fabrication process.

Figure 3.1: Ecoflex.

3.3 Structure

Structure of the soft robot will implement the pleated segment type as it is the most common and easy to build structure. By using Solidworks simulation to perform Finite Element Modelling (FEM), a soft robot with inner and outer pleated segment structure can be formed and it is clear to observe the motion of the structure and its von Mises stress as Figure 3.2 and Figure 3.3 below:

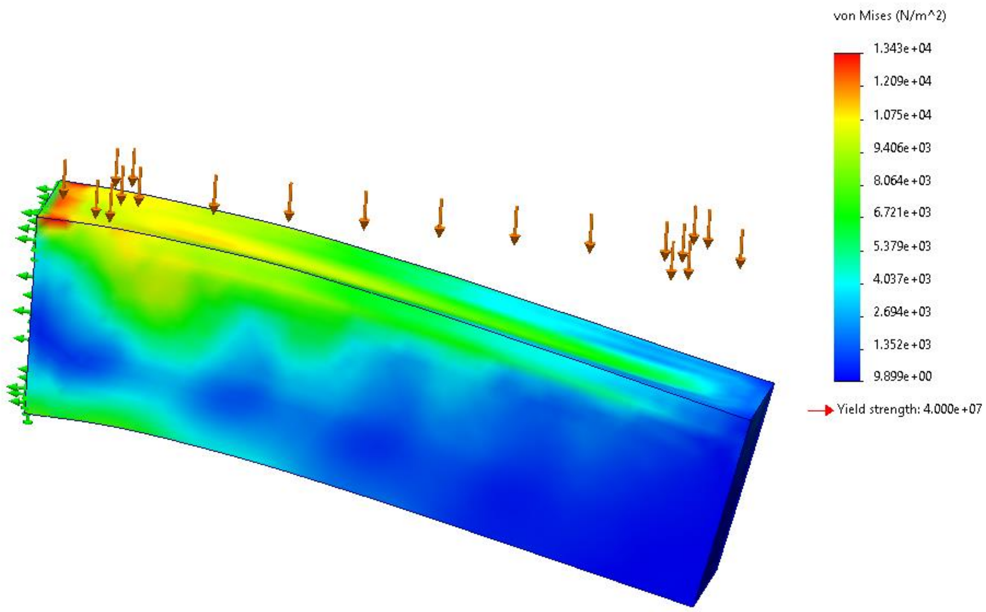

Figure 3.2: FEM simulation of inner pleated segment soft robot structure.

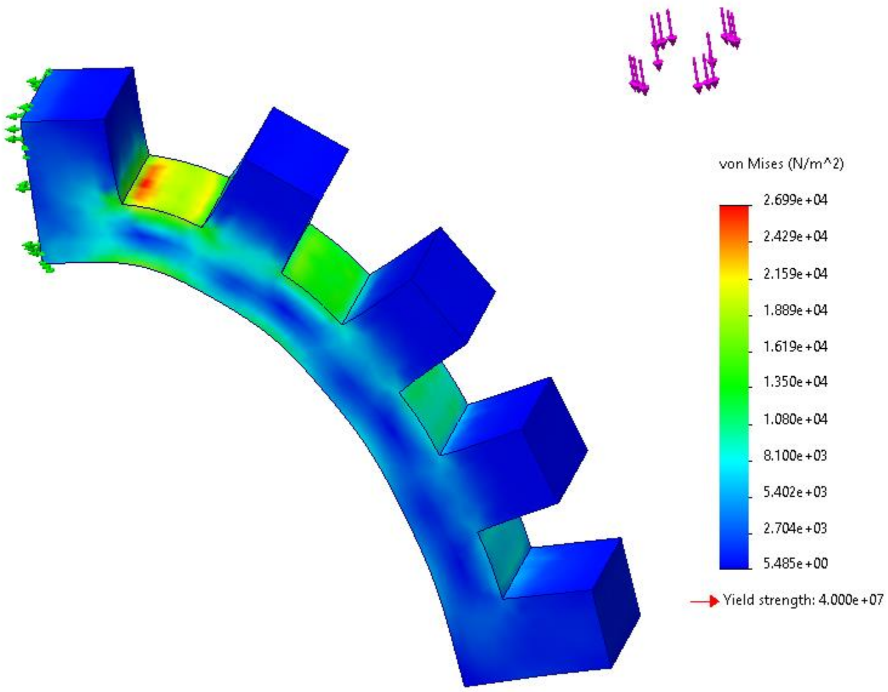

Figure 3.3: FEM simulation of outer pleated segment soft robot structure.

Figure 3.2 and Figure 3.3 show the FEM simulation of Inner and Outer pleated segment soft robot respectively. It can be observed that the bending is not obvious as the Inner pleated segment design is more solid which is the main reason affecting the bending motion of the soft robot. For the Outer pleated segment design, it can be observed that the structure bend towards the bottom as the bottom of the structure is harder. Due to the design which the air chambers have gaps between them, it will be easier for the soft robot to bend and this will ease the bending motion.

3.4 Actuation

For the actuation used in the designation of soft robot will be the pneumatic actuation. Pneumatic actuation provides all the requirements a soft robot needed during designation which is the softness and response time. The other main reason is that pneumatic actuation is safer and clean comparing with other actuation methods as it does not interact with electric or mineral oil like the hydraulic actuation which will caused dirty due to leakage. Figure 3.4 below shows the DC 12 V Electric Micro Vacuum air pumps, 12 V micro solenoid valves and the pneumatic pipes with different sizes used to build the pneumatic circuit.

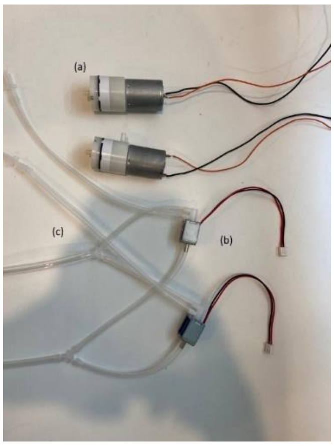

Figure 3.4: (a) DC 12 V Electric Micro Vacuum air pumps, (b) 12 V micro solenoid valves and (c) Pneumatic pipes.

From the designation above, the micro vacuum air pumps will be continuously turning ON and the micro solenoid valves will be responsible to inflate and deflate in the whole system. One of the solenoid valves acts as inlet valve by letting air flow through and enters the cavity of the soft robot, while the other valve will be acting as an exhaust valve to let the air flow out of the soft robot.

3.5 Control and Electronics

Arduino UNO board shows in Figure 3.5 below will be utilized to control the soft robot for the designation. As mentioned, Arduino board has multiple application and it has simple coding software, the soft robot's actuator can be easily controlled by the board itself with inserted commands.

Figure 3.5: Arduino UNO board.

Besides, a 2 Channel 5 V Active Low Relay Module shows in Figure 3.6 below will be implemented in building the electric circuit to control the solenoid valves by opening and closing contacts with them. In the input side of the Relay, the "GND" must be connected to the "Ground (GND)" of the Arduino UNO. While the "VCC" must be connected to the "Vin" of Arduino UNO board. Then the inputs, which are the "IN1" and "IN2" must be connected to the Analogue pins, which are the "A1" and "A2" of the Arduino UNO. The Relay can operates as Normally Opened (NO) and Normally Closed (NC) by connecting the device differently in the output of the Relay.

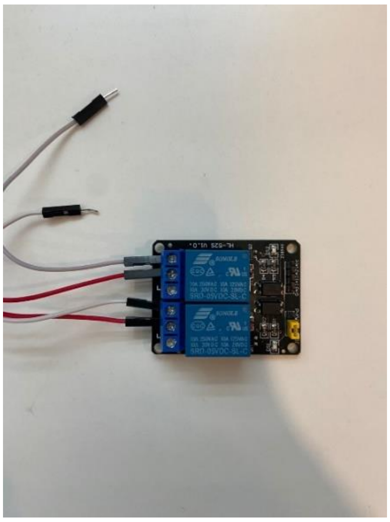

Figure 3.6: 2 Channel 5V Active Low Relay Module.

Due to Arduino UNO only provides 5 V voltage, and solenoid valves require 12V voltage to operate, a relay can be used to control the operation of 12 V solenoid valves by allowing 12 V voltage from external voltage source to connect to it when the Arduino UNO send 5 V voltage signal to the relay. Adjustable USB to DC Buck Boost Converter for DC-DC Power Supply shows in Figure 3.7 below act as a controllable external source in the electric circuit.

Figure 3.7: USB to DC Buck Boost Converter for DC-DC Power Supply.

3.6 Fabrication and Assembly of soft robot system

3.6.1 Preparation of mold

Before starting the fabrication, a mold must be design and create. The mold can be design using software like Solidworks. The mold is being designed referring the desired body structure of soft robot, which is the pleated segment type. Figure 3.8 shows the molds being designed by using Solidworks.

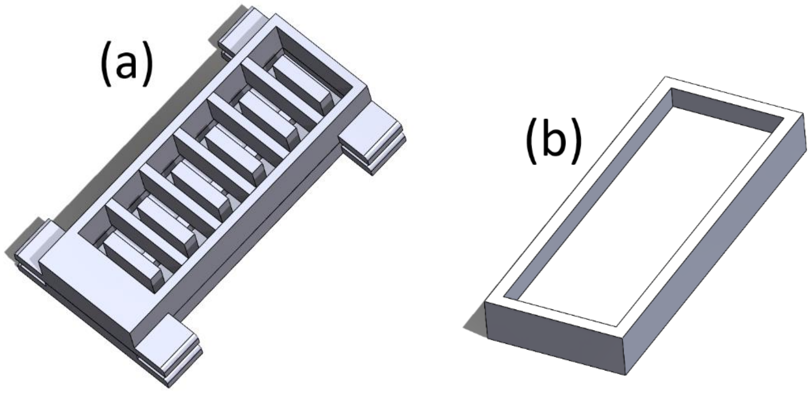

Figure 3.8: (a) Top mold and (b) Base mold.

After the mold had been designed, the mold is being created by using 3D printing technique. Figure 3.9 below is the 3D printer used for printing the mold ands.

Figure 3.9: Creality 3D printer.

3.6.2 Preparation of Ecoflex

Before the fabricating process, some of the tools and materials must be prepared to ensure the process works smoothly. Figure 3.10 below shows the materials and tools needed for fabrication process.

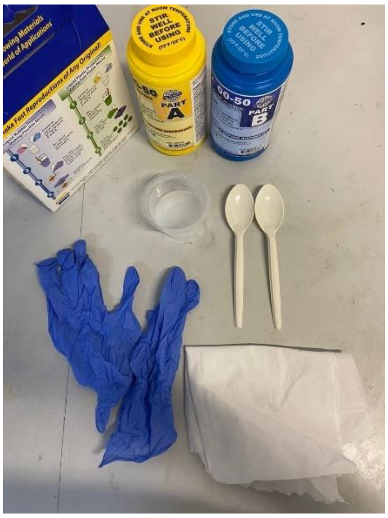

Figure 3.10: Materials and tools to be used during farbication process.

The volume and weight for part A and part B of Ecoflex 00-30 is being measured before mixing them together by using the analytical balance as shown Figure 3.11 below to obtain the best precision.

Figure 3.11: Analytical balance.

The mix ratio is set to be 1:1 by volume. Mix both slowly to avoid air bubbles. Silicone-oil can be added for lubricant purposed but it is not necessary. After mixing both mixtures, a spoon is used to mix the mixture well as shown in Figure 3.12 below. Then, the Ecoflex is ready to pour into the mold prepared.

Figure 3.12: Preparation of Ecoflex.

Figure 3.13 below shows the mixture is being poured into the mold prepared evenly. After that, the Ecoflex will be left under room temperature on a flat surface to go through curing process. Time taken for the Ecoflex to be fully cured will be around 3 hours.

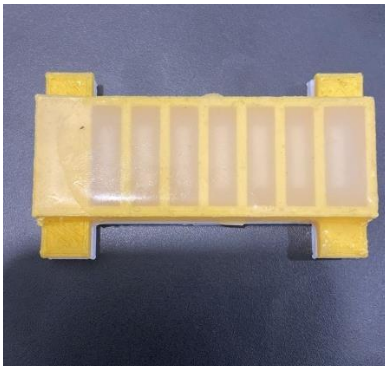

Figure 3.13: Ecoflex poured in mold.

After the Ecoflex is fully cured, it can be peeled off from the mold and the body of soft robot is then formed as shown in Figure 3.14 below.

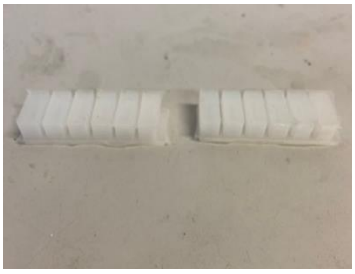

Figure 3.14: Fully cured soft robot body.

3.6.2.1 Flowchart of the fabrication process

For simplification, the flowchart of fabrication procedure is shown in Figure 3.15 below.

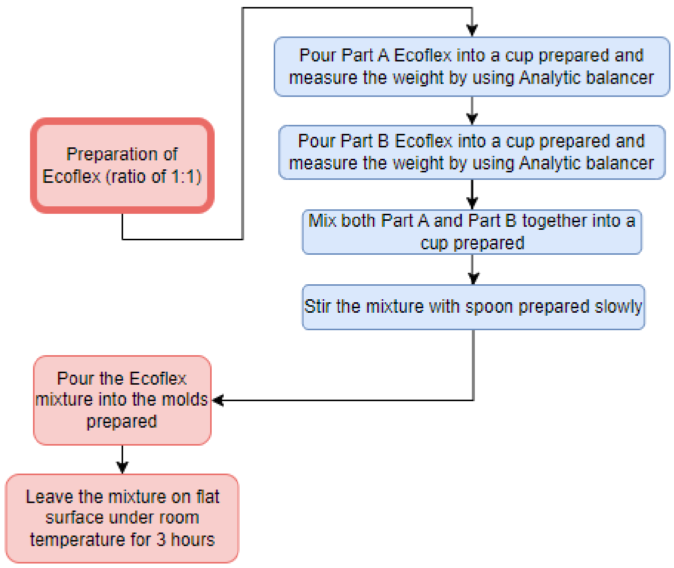

Figure 3.15: Flowchart of fabrication procedure.

3.6.3 Assembly of the soft robot circuit

Figure 3.16 below shows the proposed schematic circuit of the soft robot system. The circuit is built according to the function and properties of the electric devices. Arduino UNO will be utilized to control the relays and the solenoid valves.

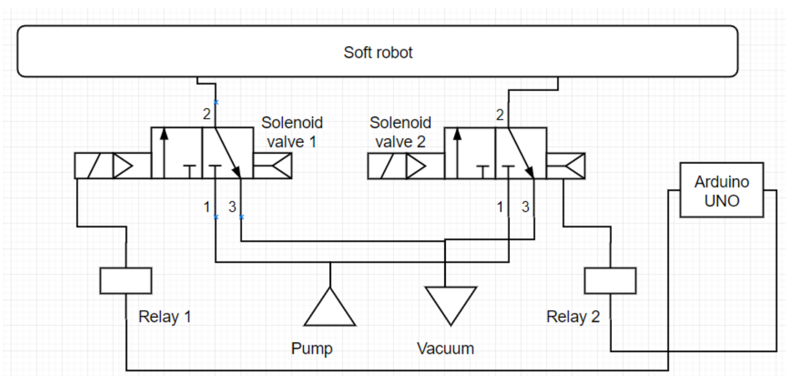

Figure 3.16: Proposed schematic circuit.

3.6.3.1 Assembly of pneumatic actuation

The pneumatic system is being assembled by using pneumatic devices prepared. One of the micro vacuum air pumps is being utilized to perform the pumping operation, while the other air pump will be performing suction operation. Both air pumps are connected to the micro solenoid valves separately as shown in Figure 3.17 below.

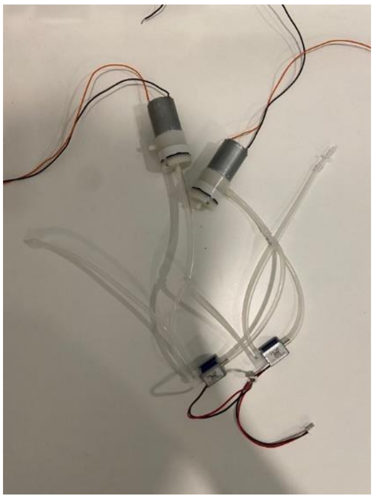

Figure 3.17: Assembled pneumatic circuit.

3.6.3.2 Assembly of the whole circuit

Figure 3.18 shows the fully assembled circuit of the soft robot system built with assembled pneumatic circuit, Arduino UNO, Channel 5 V Active Low Relay Module and USB to DC Buck Boost Converter. A Breadboard and jumper wires will be utilized to connect all the electrical devices together.

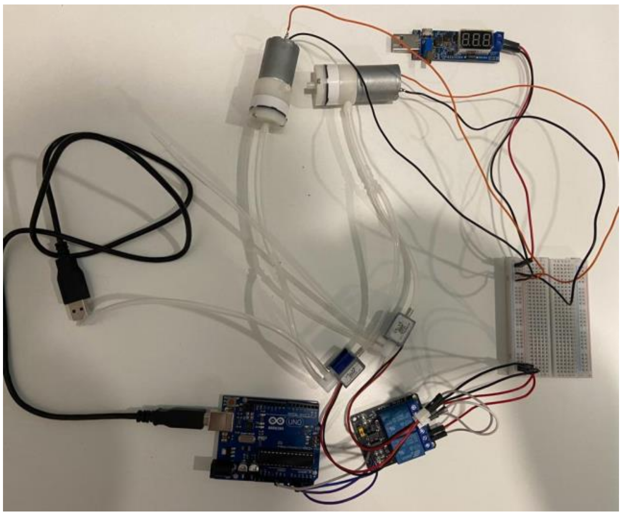

Figure 3.18: Assembled circuit of the soft robot system.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Structure of the body

There are three types of structure of the soft robot’s body being designed, which are the fully covered with inner pleated segment type, unfully covered with outer pleated segment type but thick wall and unfully covered with outer pleated segment type but thin wall. The reason for designing the fully covered and unfully covered structure is to study the stability of them and how the different structures will have different outcomes. For the unfully covered design, there will be two types of design which are the thicker wall and the thinner wall. The aim for this designation is to study the minimum thickness of wall needed to avoid breakage of the soft robot’s body during pressurization and how different thickness of wall will affect the smoothness of locomotion.

4.1.1 Fully covered with inner pleated segment type

The fully covered with inner pleated segment type is whereby the air chambers of the soft robot is fully covered with Ecoflex as shown in Figure 4.1 below. For this type of design, the soft robot will be more solid as the air chambers are not exposed outside. Due to its design, the pipes inserted on top of the soft robot will make its locomotion to be easier comparing inserting the pipes on side.

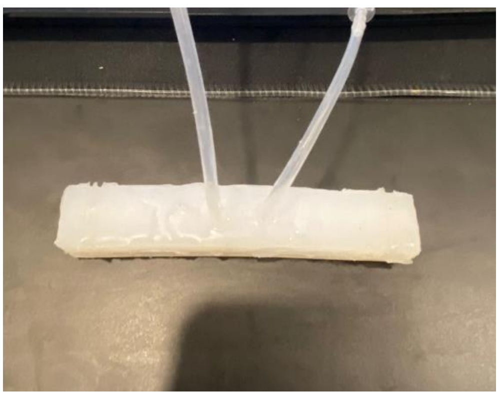

Figure 4.1: Fully covered with inner pleated segment type soft robot.

Figure 4.2 below shows the soft robot has moved a certain distance starting from the tip of the plastic ruler, where the plastic ruler is used to indicate the distance of soft robot travelled. The voltage applied to the micro pump starts from 7.0 V and slowly increases until a certain voltage to avoid the soft robot to break. The frequency applied on the solenoid valves will be ON for 500 ms and OFF for 800 ms. The sequence of the frequency applied on the solenoid valves is shown Figure 4.3 below.

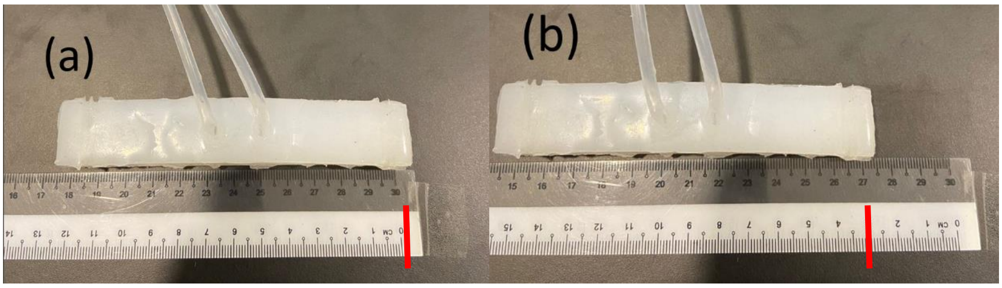

Figure 4.2: Distance travelled by Fully covered type soft robot in 60 seconds. (a) Soft robot at starting point and (b) Soft robot moved a certain distance.

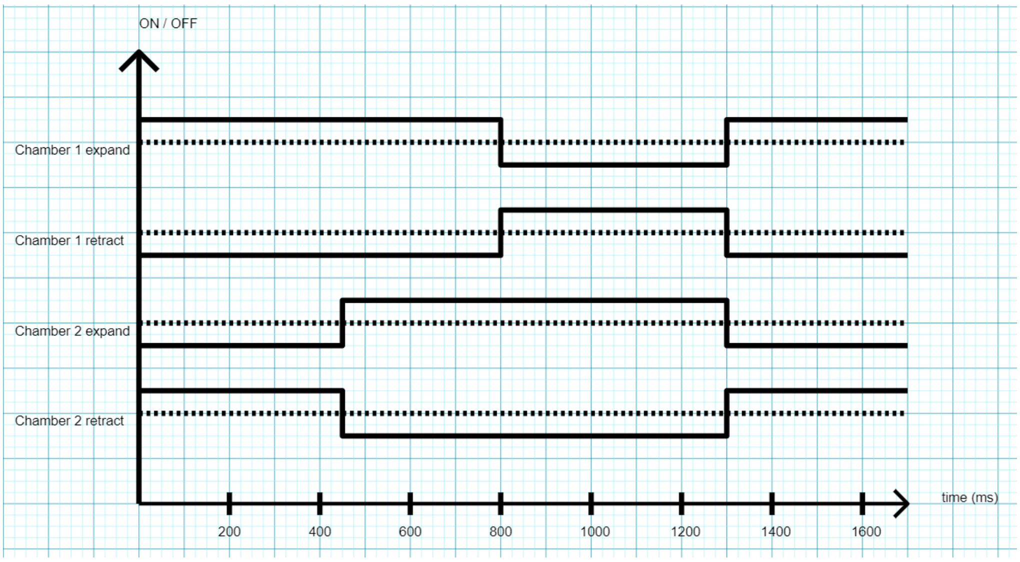

Figure 4.3: Sequence of the ON and OFF of Solenoid valves with lower frequency (Fully covered type soft robot).

Figure 4.3 shows the sequence of the ON and OFF of Solenoid valves with lower frequency applied. There will be two chambers in a soft robot and the solenoid valves will be connected to each of the chamber to control the expand and retract of the soft robot. The sequence of expand and retract will be solenoid valve connected to chamber 1 ON for a 800 ms to allow the air chamber to be pressurized, while solenoid valve connected to chamber 2 will be OFF for 500 ms. Before solenoid valve connected to chamber 1 is OFF, solenoid valve connects to chamber 2 will be ON for 800 ms. Then, the solenoid valve connects to chamber 1 will be OFF for 500 ms after it is being ON for 800 ms. This sequence will be looping for 60 seconds to measure the distance of soft robot can travel.

Table 4.1 and below shows the distance travelled by fully covered with inner pleated segment type soft robot under different voltage applied on micro pump. Figure 4.4 illustrates the graph of distance travelled by soft robot under different voltage but in lower frequency in 60 seconds.

Table 4.1: Distance travelled by soft robot under different voltage but with lower frequency in 60 seconds (Fully covered type soft robot).

Voltage applied (V)	Distance travelled (cm)
7.0	0
7.2	3
7.4	3.6
7.6	4
8.0	5.5
9.0	6

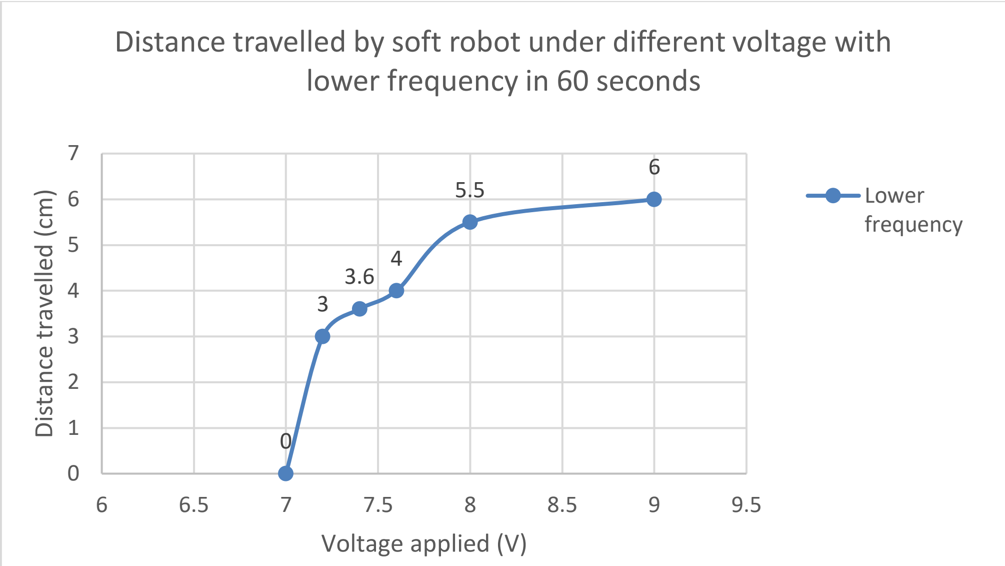

Figure 4.4: Graph of distance travelled by soft robot under different voltage with lower frequency in 60 seconds (Fully covered type soft robot).

From the Figure 4.4 above it is clear to see that when voltage applied to the micro pump increases, the distance travelled by soft robot in 60 seconds increases. But the results of distance travelled by the soft robot started to get closer around 9.0 V voltage applied. This is due to the soft robot had reached its maximum expand although pressure was kept increasing into the air chambers. So, there will be a limitation of voltage applied to the micro pump as to avoid the soft robot to be burst.

Figure 4.5 below shows that the sequence of the ON and Off of solenoid valves using different frequency applied on solenoid valve. Which is the sequence of expand and retract will be solenoid valve connected to chamber 1 ON for a 750 ms to allow the air chamber to be pressurized, while solenoid valve connected to chamber 2 will be OFF for 300 ms. Before solenoid valve connected to chamber 1 is OFF, solenoid valve connects to chamber 2 will be ON for 750 ms. Then, the solenoid valve connects to chamber 1 will be OFF for 300 ms after it is being ON for 750 ms. This sequence will be looping for 60 seconds to measure the distance of soft robot can travel.

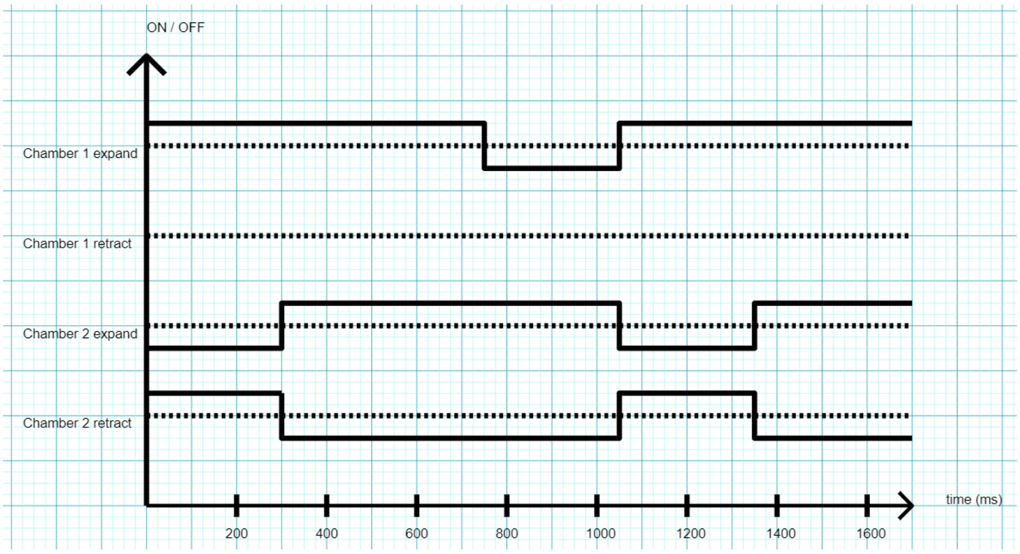

Figure 4.5: Sequence of the ON and OFF of Solenoid valves with higher frequency (Fully covered type soft robot).

Table 4.2 below shows the distance travelled by fully covered with inner pleated segment type soft robot under different voltage and higher frequency applied on solenoid valves. Figure 4.6 illustrates the graph of distance travelled by soft robot under different voltage but in higher frequency in 60 seconds.

Table 4.2: Distance travelled by soft robot under different voltage but with higher frequency in 60 seconds (Fully covered type soft robot).

Voltage applied (V)	Distance travelled (cm)
8.8	0
9.0	6.5
9.2	6.6
9.4	6.6
9.6	6.7
9.8	6.8
10.0	7.0

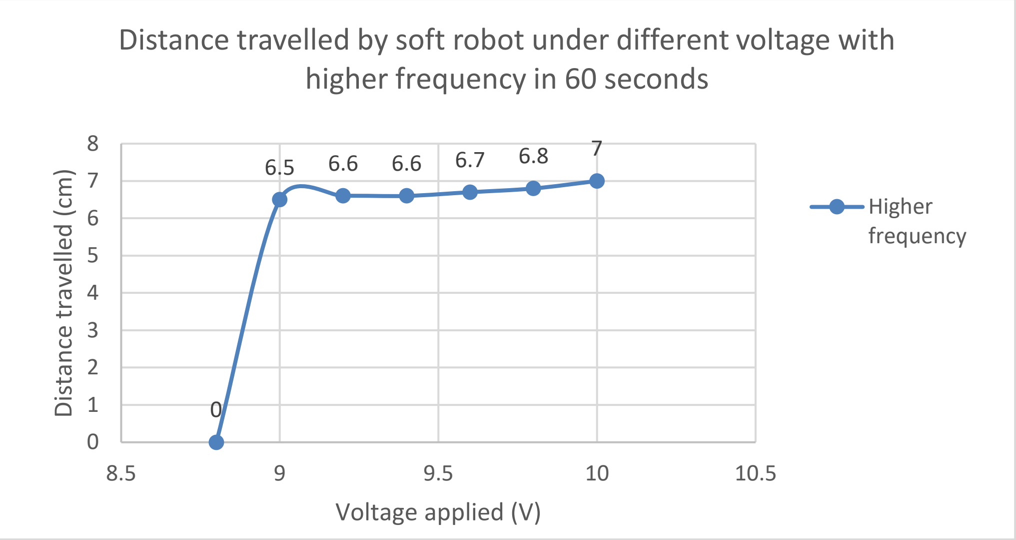

Figure 4.6: Graph of distance travelled by soft robot under different voltage with higher frequency in 60 seconds (Fully covered type soft robot).

From the Figure 4.6 above it is clear to see that when voltage applied to the micro pump increases, the distance travelled by soft robot in 60 seconds increases propotionally. But the results of distance travelled by the soft robot are very close for all the voltage applied on the solenoid valve and there will be a limitation of voltage can be applied. This is due to the soft robot had reached its maximum expand in the beginning due to high voltage applied. So, if the voltage applied continue to increase until a certain value, the body of the soft robot might burst. Figure 4.7 below shows the fully covered type soft robot maneuvering in confined space. Cardboard is utilized to represent as confined space, where the height and width are 6.5 cm and 3 cm respectively.

Figure 4.7: Fully covered inner pleated segment type soft robot maneuvering in confined space.

4.1.2 Unfully covered with outer pleated segment type

The unfully covered with outer pleated segment type will be separated into two types, which are the thicker wall and thinner wall. Figure 4.8 below shows the two types of soft robot which having different wall thickness. From both unfully covered designs, it is clear to observe that the air chambers are exposed outside. Both designs will have pipes inserted on the side to ease their movement.

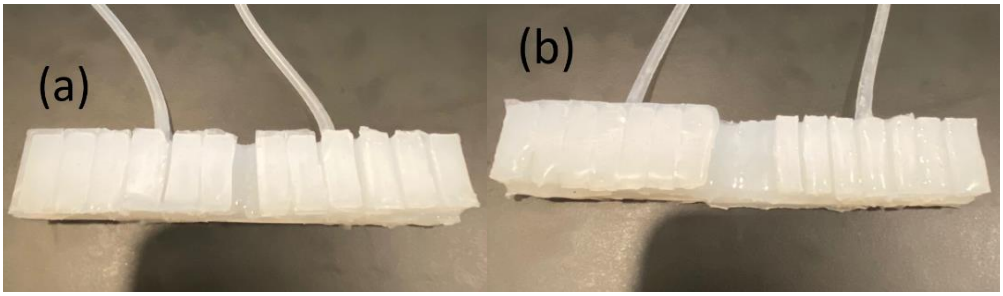

Figure 4.8: Unfully covered with outer pleated segment type soft robot. (a) Design with thicker wall and (b) Design with thinner wall.

Figure 4.9 below shows the distance travelled by soft robot having design with thicker wall from starting point. While Figure 4.10 below shows the distance travelled soft robot having design with thinner wall. Both of the soft robot will start from the tip of the plastic ruler, where the plastic ruler is used to indicate the distance of soft robot travelled. The voltage applied to the micro pump starts from 8.0 V for the thicker wall and 7.7 V for the thinner wall and the voltage will be slowly increased until a certain amount. The sequence of the frequency applied on the solenoid valves for both design is same as the frequency applied on the solenoid valves for the fully covered inner pleated segment design soft robot, which includes higher and lower frequency applied on the solenoid valves.

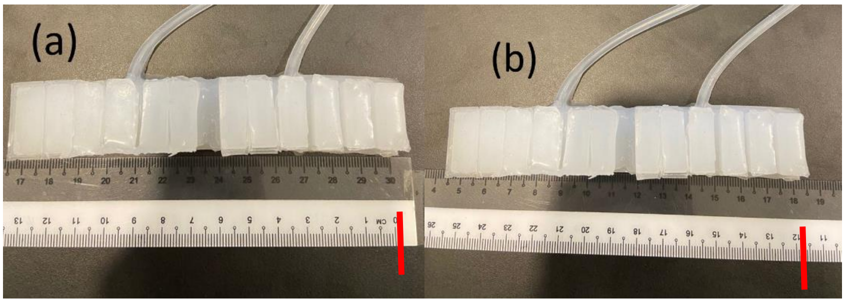

Figure 4.9: (a) Soft robot at starting point and (b) Soft robot moved a certain distance (Design with thicker wall).

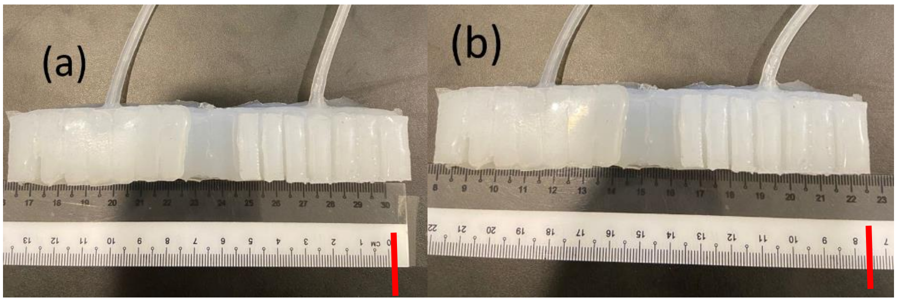

Figure 4.10: (a) Soft robot at starting point and (b) Soft robot moved a certain distance (Design with thinner wall).

Table 4.3 and Table 4.4 below show the distance travelled the soft robot having thicker and thinner wall respectively under different voltage and lower frequency applied on solenoid valves. While Figure 4.11 and Figure 4.12 below illustrate the graph of distance travelled with lower frequency under different voltage applied.

Table 4.3: Distance travelled by soft robot under different voltage but with lower frequency in 60 seconds (Design with thicker wall).

Voltage applied (V)	Distance travelled (cm)
7.8	0
8.0	11.5
8.2	11.6
8.4	12.0
8.6	12.0
8.8	12.0
9.0	12.0

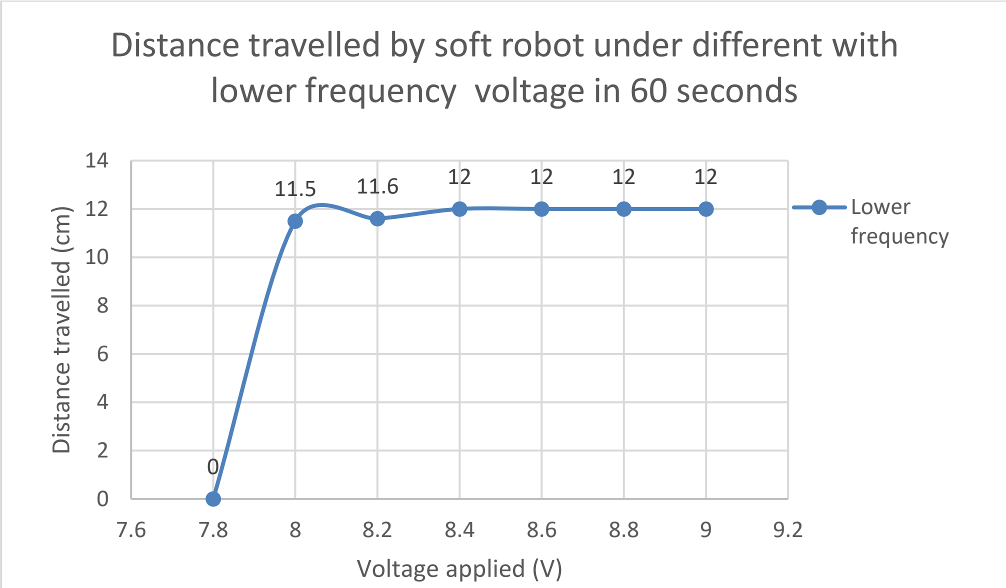

Figure 4.11: Graph of distance travelled by soft robot under different voltage with lower frequency in 60 seconds (Design with thicker wall).

Table 4.4: Distance travelled by soft robot under different voltage but with lower frequency in 60 seconds (Design with thinner wall).

Voltage applied (V)	Distance travelled (cm)
7.6	0
7.7	8.0
7.8	8.0
7.9	8.1
8.0	8.1

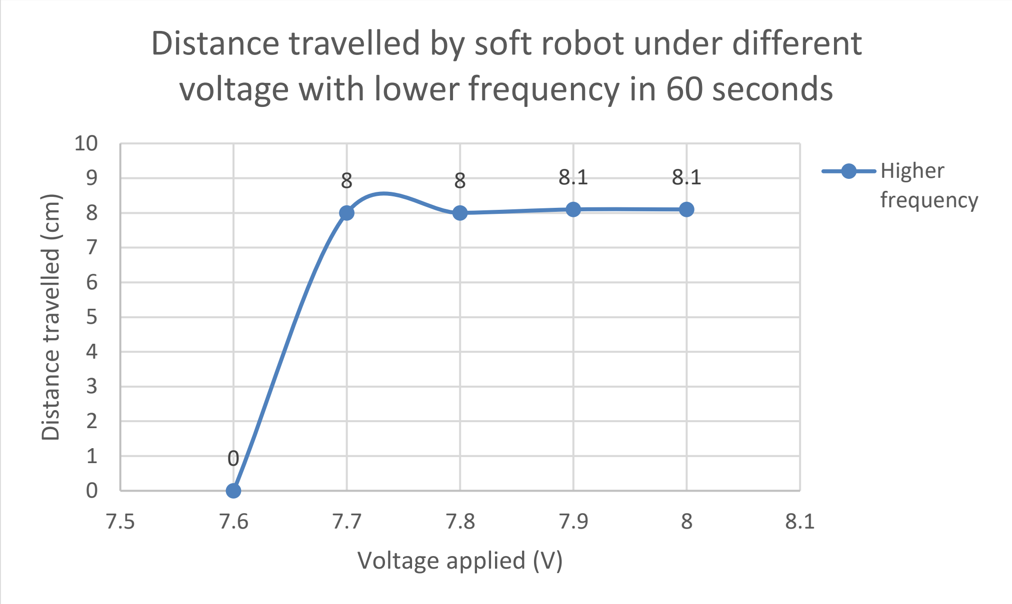

Figure 4.12: Graph of distance travelled by soft robot under different voltage with lower frequency in 60 seconds (Design with thinner wall).

From both of the results above it can observe that the results for every voltage applied does not varies a lot. And the optimum voltages both the design required for smooth locomotion is between range of 7 V to 9 V.

Table 4.5 and Table 4.6 below shows the distance travelled the soft robot having thicker and thinner wall respectively under different voltage with higher frequency applied. While Figure 4.13 and Figure 4.14 below illustrate the graph of distance travelled under different voltage applied.

Table 4.5: Distance travelled by soft robot under different voltage but with higher frequency in 60 seconds (Design with thicker wall).

Voltage applied (V)	Distance travelled (cm)
7.8	0
8.0	7
8.2	7.6
8.4	8
8.6	10
8.8	11.7
9.0	12.5

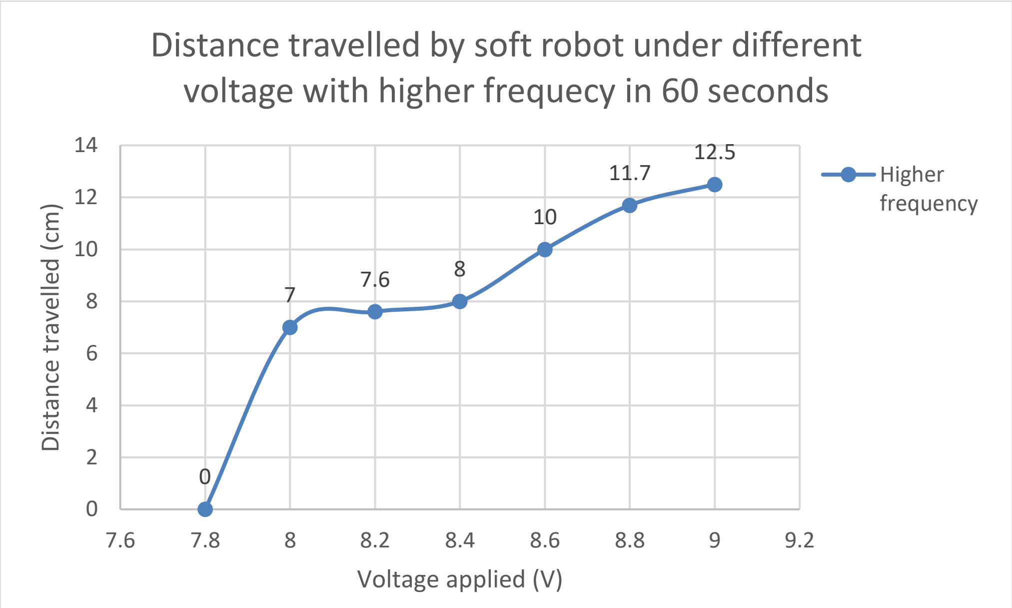

Figure 4.13: Graph of distance travelled by soft robot under different voltage with higher frequency in 60 seconds (Design with thicker wall).

Table 4.6: Distance travelled by soft robot under different voltage but with higher frequency in 60 seconds (Desing with thinner wall).

Voltage applied (V)	Distance travelled (cm)
7.8	0
8.0	10.8
8.2	11.0
8.4	11.1
8.6	11.0

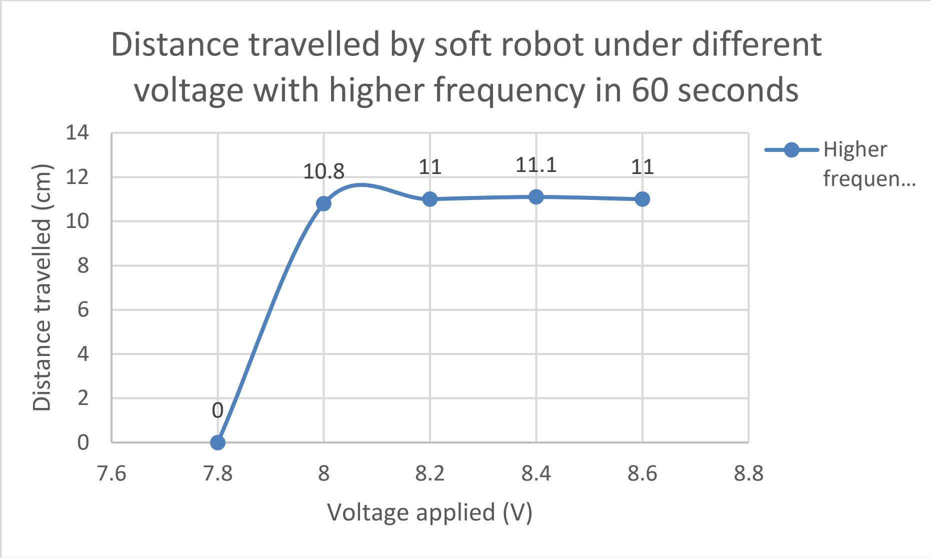

Figure 4.14: Graph of distance travelled by soft robot under different voltage with higher frequency in 60 seconds (Design with thinner wall).

Figure 4.15 and Figure 4.16 below show the unfully covered type with thicker and thinner wall soft robot maneuvering in confined space respectively. The height and width of the confined space are 6 cm and 3 cm respectively.

Figure 4.15: Unfully covered outer pleated segment type with thicker wall soft robot maneuvering in confined space.

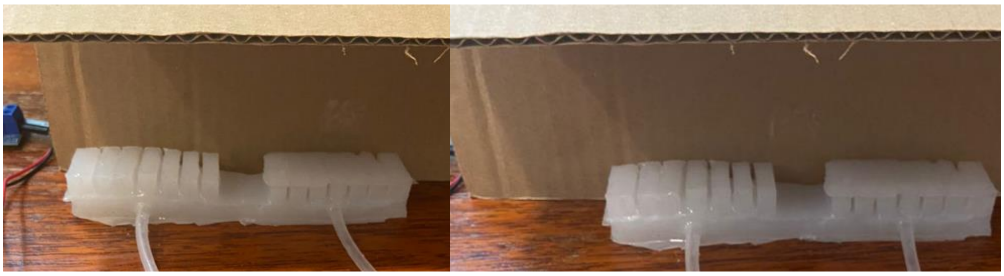

Figure 4.16: Unfully covered outer pleated segment type with thinner wall soft robot maneuvering in confined space.

4.2 Summary

Comparing the results for all the frequency applied on the solenoid valve, the higher voltage applied on the micro pump, the further the distance soft robot can travel. For the fully covered inner pleated segment design, for lower frequency applied, the maximum distance travelled by soft robot is 6 cm only in 60 seconds. Whereas for higher frequency the maximum distance travelled by soft robot is 7 cm. Both of the outcome results have not much difference. The reason is because the fully covered design will cause the soft robot to become more solid and this will cause the resistance to its movement as the wall of the body is thick.

From observing the results of the unfully covered design, both of the thicker and thinner wall design have better outcome results compared to the fully covered one which both of their maximum distance more than the fully covered design in 60 seconds. But by observing Table 4.4, the maximum distance for the thicker and thinner wall design soft robot with low frequency applied in solenoid valves can travel is only 12.0 cm and 8.1 cm respectively. The main reason is the frequency applied are very low and because that there will be limitation of voltage that are able to apply to both designs to avoid burst, both reasons will affect the distance the soft robots are able to travel. Besides, when applying higher frequency, although both unfully covered design soft robots can travel a little bit further, but the maximum voltage they are able to apply is still limited to a certain value, which are around 9 V for the thicker wall design and 8.6 V for the thinner wall design.

Among three of the designs, the fully covered one will have more stable locomotion and not easy to break but it moves very slow. It can also withstand higher voltages applied on the micro pump comparing with the other two designs. But by comparing with the results of distance of soft robot travelled, the unfully covered outer pleated segment with thicker wall can travel further in 60 seconds comparing with other two designs. This is because the outer pleated segment structure will have a smoother bending comparing with the fully covered inner pleated segment structure. It can be bent a lot and it will form a very nice bending curve during pressurization between the chambers. Besides, thicker wall will cause the soft robots to withstand higher pressure. Thus, higher voltage is able to apply and the distance travel by the soft robot will be further. Overall, the unfully covered outer pleated segment design with thicker wall is the best design comparing with two other designs. Table 4.7 below summarize the comparison results for the three different kinds of soft robots being designed in a table.

Table 4.7: Comparison between three different kinds of soft robots.

Structure	Fully covered	Unfully covered with thicker wall	Unfully covered with thinner wall
	Lower frequency (500ms and 800ms)		
Minimum voltage (V)	7.2	8.0	7.7
Maximum voltage (V)	9.0	9.0	8.0
Minimum distance travelled (cm)	3	11.5	8.0
Maximum distance travelled (cm)	6	12.0	8.1
	Higher frequency (350ms and 700ms)		
Minimum voltage (V)	9.0	8.0	8.0
Maximum voltage (V)	10.0	9.0	8.6
Minimum distance travelled (cm)	6.5	7	10.8
Maximum distance travelled (cm)	7.0	12.5	11.0

By comparing the most perfect design obtained during this project with soft robot designed by others, there will be some differences in the results. Figure 4.17 below shows two parts of the soft robot connected side by side which designed by others. While Table 4.8 below shows the comparison between the most perfect soft robot designed in this project with others.

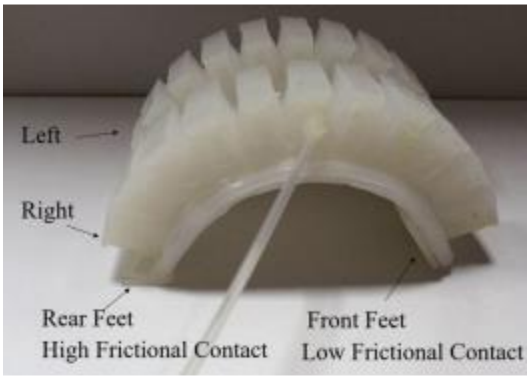

Figure 4.17: Two parts of soft robot connected side by side (Wang et al., 2019).

Table 4.8: Comparison of soft robot in this project with others.

Unfully covered with thicker wall	Two parts connected side by side (Other's design)	Two parts connected linearly (Design done by this project)
Turning motion	Yes	No
Distance travelled in 20 seconds (cm)	2	4.5
Able to travel in tight spaces	Yes	Yes

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, the objectives of this project are achieved. The soft robots designed were able to perform linear locomotion and travel under confined space. The actuating mechanism of the soft robot was done properly and under-controlled. From this project, the mechanism of soft robot was understood well by doing trial and error to obtain the optimal results. As soft robot’s body is soft and stretchable, it is quite a challenge to control the pressure applied on to it to avoid breakage. Overall, from the results obtained during experiments had clearly shown the different types of structure of the body soft robot will have different outcomes and the frequencies and voltage applied will also affect the smoothness of its locomotion.

5.2 Problem encountered

During the designation of soft robot, the thickness of wall needed to avoid the soft robot to break during pressurization was hard to expect. Trial and error were done several times to obtain the optimal results. The piping of the soft robot was also one of the challenges faced during this project. Besides, due to lack of knowledge of implementing the software to analyse the motion and stress of the soft robot when force applied on it during pressurization, a lot of time was consumed to learn how does the software works and how to perform simulation by using Solidworks. Next, during fabrication process, due to lack of experience, the correct amount of Ecoflex needed to be poured into the mold prepare to fill it up as to avoid wastage was also one of the challenges faced. But after going through few times of experiments, the problem faced was solved. Finally, the electric circuit to control the movement of soft robot was one of the biggest problems faced in this project. Due to lack of experience in coding the Arduino UNO and circuit assemble, a great amount of time was consumed on the coding part and learning the circuit theory of the electronic devices.

5.3 Recommendations

There are several ways to overcome the problems encountered in this project. To understand the thickness of wall required to avoid breakage of the soft robot, by using simulation software like Abaqus or Solidworks, the stress and strain due to different forces applied can be analyse. By doing research and study to understand how stress and strain including the properties of Ecoflex, the maximum forces that applied can find approximately. For the piping section, the problem can be overcome by doing different types of piping. For instance, inserting the pipes on top or side of the soft robot to obtain the best position for the pipes’ insertion. Fabrication problem can be solved by doing more experiments to gain experience and the problem can be overcome by seeking adviced from experts or senior students. Lastly, the problem of coding for Arduino UNO can be reduced by doing trial and error and seek for opinions from experts through online, for example, Github and Quora.

REFERENCES

Albu-Schaffer, A., Fischer, M., Schreiber, G., Schoeppe, F. & Hirzinger, G. Soft robotics: what cartesian stiffness can obtain with passively compliant, uncoupled joints? 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566), 2004. IEEE, 3295-3301.

Ariano, P., Accardo, D., Lombardi, M., Bocchini, S., Draghi, L., De Nardo, L., Fino, P. J. J. O. a. B. & Materials, F. 2015. Polymeric materials as artificial muscles: an overview. 13**,** 1-9.

Ariati, R., Sales, F., Souza, A., Lima, R. A. & Ribeiro, J. J. P. 2021. Polydimethylsiloxane composites characterization and its applications: a review. 13**,** 4258.

Bar-Cohen, Y. Electroactive polymers as artificial muscles-reality and challenges. 19th AIAA Applied Aerodynamics Conference, 2001. 1492.

Boblan, I., Bannasch, R., Schwenk, H., Prietzel, F., Miertsch, L. & Schulz, A. A human-like robot hand and arm with fluidic muscles: Biologically inspired construction and functionality. Embodied Artificial Intelligence: International Seminar, Dagstuhl Castle, Germany, July 7-11, 2003. Revised Papers, 2004. Springer, 160-179.

Camarillo, D. B., Milne, C. F., Carlson, C. R., Zinn, M. R. & Salisbury, J. K. J. I. T. O. R. 2008. Mechanics modeling of tendon-driven continuum manipulators. 24, 1262-1273.

Chen, G., Pham, M. T., Redarce, T. J. R. & Systems, A. 2009. Sensor-based guidance control of a continuum robot for a semi-autonomous colonoscopy. 57, 712-722.

Cianchetti, M., Calisti, M., Margheri, L., Kuba, M., Laschi, C. J. B. & Biomimetics 2015. Bioinspired locomotion and grasping in water: the soft eight-arm OCTOPUS robot. 10, 035003.

Dong, L., Agarwal, A. K., Beebe, D. J. & Jiang, H. J. N. 2006. Adaptive liquid microlenses activated by stimuli-responsive hydrogels. 442, 551-554.

Eitel, L. 2018. Shape-memory alloys linear actuators: A new option for positioning [Online]. Design World. Available: https://www.designworldonline.com/shape-memory-alloys-linear-actuators-a-new-option-for-positioning/ [Accessed 7 September 2023].

Gao, L., Guo, G., Liu, M., Tang, Z., Xie, L. & Huo, Y. J. R. A. 2017. Multi-responsive, bidirectional, and large deformation bending actuators based on borax cross-linked polyvinyl alcohol derivative hydrogel. 7, 40005-40014.

Guanjun, B., Pengfei, Y., Zonggui, X., Kun, L., Zhiheng, W., Libin, Z., Qinghua, Y. J. I. J. O. A. & Engineering, B. 2017. Pneumatic bio-soft robot module: Structure, elongation and experiment. 10, 114-122.

Hu, Z., Zhang, X. & Li, Y. J. S. 1995. Synthesis and application of modulated polymer gels. 269, 525-527.

Jani, J. M., Leary, M., Subic, A., Gibson, M. a. J. M. & Design. 2014. A review of shape memory alloy research, applications and opportunities. 56, 1078-1113.

Jeong, S. H., Hagman, A., Hjort, K., Jobs, M., Sundqvist, J. & Wu, Z. J. L. O. a. C. 2012. Liquid alloy printing of microfluidic stretchable electronics. 12, 4657-4664.

Jeong, S. H., Hjort, K. & Wu, Z. J. S. R. 2015. Tape transfer atomization patterning of liquid alloys for microfluidic stretchable wireless power transfer. 5, 8419.

Jihong, Y., Peipei, S., Xinbin, Z. & Jie, Z. J. J. O. M. E. 2018. Review of biomimetic mechanism, actuation, modeling and control in soft manipulators. 54, 1-14.

Katzschmann, R. K., De Maille, A., Dorhout, D. L. & Rus, D. Cyclic hydraulic actuation for soft robotic devices. 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016. IEEE, 3048-3055.

Keplinger, C., Sun, J.-Y., Foo, C. C., Rothemund, P., Whitesides, G. M. & Suo, Z. J. S. 2013. Stretchable, transparent, ionic conductors. 341, 984-987.

Kim, Y. S., Liu, M., Ishida, Y., Ebina, Y., Osada, M., Sasaki, T., Hikima, T., Takata, M. & Aida, T. J. N. M. 2015. Thermoresponsive actuation enabled by permittivity switching in an electrostatically anisotropic hydrogel. 14, 1002-1007.

Kornbluh, R., Pelrine, R., Eckerle, J. & Joseph, J. Electrostrictive polymer artificial muscle actuators. Proceedings. 1998 IEEE international conference on robotics and automation (Cat. No. 98CH36146), 1998. IEEE, 2147-2154.

Krishna, S., Nagarajan, T. & Rani, A. J. J. O. a. S. 2011. Review of current development of pneumatic artificial muscle. 11, 1749-1755.

Laschi, C., Cianchetti, M. J. F. I. B. & Biotechnology 2014. Soft robotics: new perspectives for robot bodyware and control. 2, 3.

Lee, H. R., Kim, C. C. & Sun, J. Y. J. a. M. 2018. Stretchable ionics–a promising candidate for upcoming wearable devices. 30, 1704403.

Li, X., Wang, Y., Xu, M., Shi, Y., Wang, H., Yang, X., Ying, H. & Zhang, Q. J. J. O. a. P. S. 2021. Polymer electrets and their applications. 138, 50406.

Lu, Y., Zhou, K., Ding, Y., Zhang, G. & Wu, C. J. P. C. C. P. 2010. Origin of hysteresis observed in association and dissociation of polymer chains in water. 12, 3188-3194.

Marchese, A. D., Onal, C. D. & Rus, D. J. S. R. 2014. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. 1, 75-87.

Martinez, R. V., Branch, J. L., Fish, C. R., Jin, L., Shepherd, R. F., Nunes, R. M., Suo, Z. & Whitesides, G. M. J. a. M. 2013. Robotic tentacles with three‐dimensional mobility based on flexible elastomers. 25, 205-212.

Noritsugu, T., Kubota, M., Yoshimatsu, S. J. J. O. R. & Mechatronics 2001. Development of pneumatic rotary soft actuator made of silicone rubber. 13, 17-22.

Ohm, C., Brehmer, M. & Zentel, R. J. a. M. 2010. Liquid crystalline elastomers as actuators and sensors. 22, 3366-3387.

Olvera, D. & Monaghan, M. G. J. a. D. D. R. 2021. Electroactive material-based biosensors for detection and drug delivery. 170, 396-424.

Omnexus. Silicone Rubber: Complete Guide on Highly Durable Elastomer [Online]. Omnexus. Available: https://omnexus.specialchem.com/selection-guide/silicone-rubber-elastomer [Accessed 7 September 2023].

Ongaro, F., Scheggi, S., Yoon, C., Den Brink, F. V., Oh, S. H., Gracias, D. H. & Misra, S. J. J. O. M.-B. R. 2017. Autonomous planning and control of soft untethered grippers in unstructured environments. 12, 45-52.

Robinson, G. & Davies, J. B. C. The parallel bellows actuator. Robotica 98, 1998.

Rodrigue, H., Wang, W., Han, M.-W., Kim, T. J. & Ahn, S.-H. J. S. R. 2017. An overview of shape memory alloy-coupled actuators and robots. 4, 3-15.

Rodrigues, L. & Mota, M. 2016. Bioinspired materials for medical applications, Woodhead Publishing.

Sahin, O., Ashokkumar, M. & Ajayan, P. M. 2018. Micro-and nanopatterning of biomaterial surfaces. Fundamental Biomaterials: Metals. Elsevier.

Salleo, A. J. M. T. 2007. Charge transport in polymeric transistors. 10, 38-45.

Sappati, K. K. & Bhadra, S. J. S. 2018. Piezoelectric polymer and paper substrates: A review. 18, 3605.

Schulz, S., Pylatiuk, C. & Bretthauer, G. A new ultralight anthropomorphic hand. Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation (Cat. No. 01CH37164), 2001. IEEE, 2437-2441.

Shaikh, S. F., Shaikh, F. F., Shaikh, A. V., Ubaidullah, M., Al-Enizi, A. M., Pathan, H. M. J. J. O. P. & Solids, C. O. 2021. Electrodeposited more-hydrophilic nano-nest polyaniline electrodes for supercapacitor application. 149, 109774.

Shukrun, E., Cooperstein, I. & Magdassi, S. J. a. S. 2018. 3D‐Printed organic‐ceramic complex hybrid structures with high silica content. 5, 1800061.

Sun, J.-Y., Zhao, X., Illeperuma, W. R., Chaudhuri, O., Oh, K. H., Mooney, D. J., Vlassak, J. J. & Suo, Z. J. N. 2012. Highly stretchable and tough hydrogels. 489, 133-136.

Suzumori, K., Iikura, S. & Tanaka, H. J. I. C. S. M. 1992. Applying a flexible microactuator to robotic mechanisms. 12, 21-27.

Tondu, B. & Lopez, P. J. I. C. S. M. 2000. Modeling and control of McKibben artificial muscle robot actuators. 20, 15-38.

Trimmer, B. A., Takesian, A. E., Sweet, B. M., Rogers, C. B., Hake, D. C. & Rogers, D. J. Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots. 7th international symposium on technology and the mine problem, 2006. Monterey, CA: Mine Warfare Association, 1-10.

Turner, B. N., Strong, R. & Gold, S. a. J. R. P. J. 2014. A review of melt extrusion additive manufacturing processes: I. Process design and modeling. 20, 192-204.

Wakimoto, S., Ogura, K., Suzumori, K. & Nishioka, Y. Miniature soft hand with curling rubber pneumatic actuators. 2009 IEEE International Conference on Robotics and Automation, 2009. IEEE, 556-561.

Wang, L., Iida, F. J. I. R. & Magazine, A. 2015. Deformation in soft-matter robotics: A categorization and quantitative characterization. 22, 125-139.

Wissman, J., Lu, T. & Majidi, C. Soft-matter electronics with stencil lithography. SENSORS, 2013 IEEE, 2013. IEEE, 1-4.

Yang, C. & Suo, Z. J. N. R. M. 2018. Hydrogel ionotronics. 3, 125-142.

Yuk, H., Lin, S., Ma, C., Takaffoli, M., Fang, N. X. & Zhao, X. J. N. C. 2017. Hydraulic hydrogel actuators and robots optically and sonically camouflaged in water. 8, 14230.

Yuk, H., Lu, B. & Zhao, X. J. C. S. R. 2019. Hydrogel bioelectronics. 48, 1642-1667.

Zheng, J., Xiao, P., Le, X., Lu, W., Théato, P., Ma, C., Du, B., Zhang, J., Huang, Y. & Chen, T. J. J. O. M. C. C. 2018. Mimosa inspired bilayer hydrogel actuator functioning in multi-environments. 6, 1320-1327.

APPENDICES

APPENDIX A: Arduino code

Code for higher frequency applied in solenoid valves

```
const int RELAY_PIN1 = A1;  // the Arduino pin, which connects to the IN pin of relay
const int RELAY_PIN2 = A2;

// the setup function runs once when you press reset or power the board
void setup() {
  pinMode(RELAY_PIN1, OUTPUT);
  pinMode(RELAY_PIN2, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(RELAY_PIN1, LOW);
  delay(500);
  digitalWrite(RELAY_PIN2, HIGH);
  delay(800);
  digitalWrite(RELAY_PIN1, HIGH);
  delay(800);
  digitalWrite(RELAY_PIN2, LOW);
  delay(500);
}
```

Code for lower frequency applied in solenoid valves

```
const int RELAY_PIN1 = A1;  // the Arduino pin, which connects to the IN pin of relay
const int RELAY_PIN2 = A2;

// the setup function runs once when you press reset or power the board
void setup() {
  pinMode(RELAY_PIN1, OUTPUT);
  pinMode(RELAY_PIN2, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(RELAY_PIN1, LOW);
  delay(300);
  digitalWrite(RELAY_PIN2, HIGH);
  delay(750);
  digitalWrite(RELAY_PIN1, HIGH);
  delay(750);
  digitalWrite(RELAY_PIN2, LOW);
  delay(300);
}
```