MUSCLE-ALIKE ACTUATOR BASED ON IONIC POLYMER METAL COMPOSITE (IPMC)

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A project report submitted in partial fulfilment of requirements for the award of Bachelor of Engineering (Hons.) Mechatronics Engineering

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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.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"MUSCLE-ALIKE ACTUATOR BASED ON IONIC POLYMER METAL COMPOSITE (IPMC)"** was prepared by **ONG YON YUAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechatronics Engineering at Universiti Tunku Abdul Rahman.

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MUSCLE-ALIKE ACTUATOR BASED ON IONIC POLYMER METAL COMPOSITE (IPMC)

ABSTRACT

Ionic polymer metal composites(IPMC) is an ionic polymer film with two electrode plate coated or plated on to both surfaces of the polymer which directly opposite to each other. When there are small amount of voltage apply across both electrode , the IPMC will bend toward positive electrode. IPMC is used as actuator and further explore its potential in micropositioner applications. Monolithic IPMC micropositioner was fabricated using silver mirror method (chemical plating) with the aid of photolithography. Numerical modelling was performed to study the deflection profile prior before fabrication. The behaviour of the developed IPMC micropositioner was tested using laser displacement sensor in performing z-axis movement and tilting movement. The experiment results show the IPMC micropositioner deflects ~1 mm in z-axis movement and ~1.22 degree of tilting angle for both upward and downward bending.

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. Chee Pei Song for his invaluable advice, guidance and his enormous patience throughout the development of the research and this final year report.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Ionic polymer metal composites (IPMC) consists of an ion exchange polymer film and two conducting materials as electrodes. Both electrodes are plated on both side of the ionic polymer film. It can act as an actuator or as a sensor (Shahinpoor, 2015). When a small voltage difference is applied across both electrodes, the IPMC will bend toward the positive side of the voltage applied. This behaviour on the other hand, IPMC creates a voltage difference when it is under stress or being bend, making it as a suitable candidate as a sensor. Normally, the ionic polymer used in IPMC technologies is Nafion and the electrodes are normally made of conductive material such as platinum, gold, silver, carbon composite and so on (Shahinpoor, 2015, Lian et al., 2010). The chemical formula of the Nafion and its structure are respectively shown in Figure 1.1 and Figure 1.2.

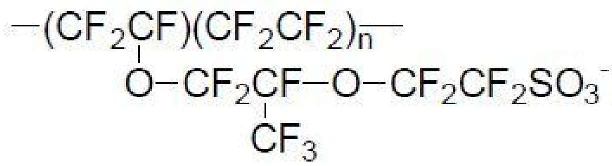


Figure 1.1: Nafion Chemical Formula (Bar-Cohen, 2004)

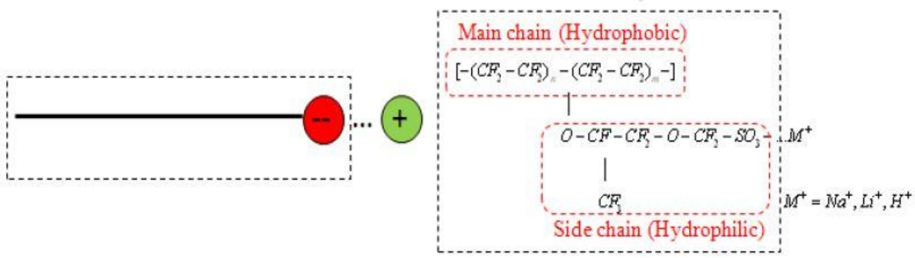


Figure 1.2: Nafion Chemical Structure (Wei and Su, 2012)

The working principle of IPMC as an actuator can be related to electromechanical transduction. The performance of the IPMC actuator are affected by the nature of the backbone ionomer, structure of electrodes, cations and the level of hydration (Feng and Liu, 2014). When a voltage difference is applied to the IPMC, the hydrated cations will move toward the negative terminal of the electrode. This will cause the volume near the positive electrode to decrease and the IPMC will bend toward the positive terminal (Wei and Su, 2012). The cation used in IPMC are Sodium ion, Lithium ion or Hydrogen ion which shown in Figure 1.2. On the other hand, the principle of sensing is related to Nernst-Planck phenomena. When there are mechanical deformation of the IPMC strip, the deformation will cause the cations in the IPMC strip to move from compressed areas to areas that are expending which will generate a electrical signal (Shahinpoor, 2015). The sensing and actuating mechanism are shown in Figure 1.3.

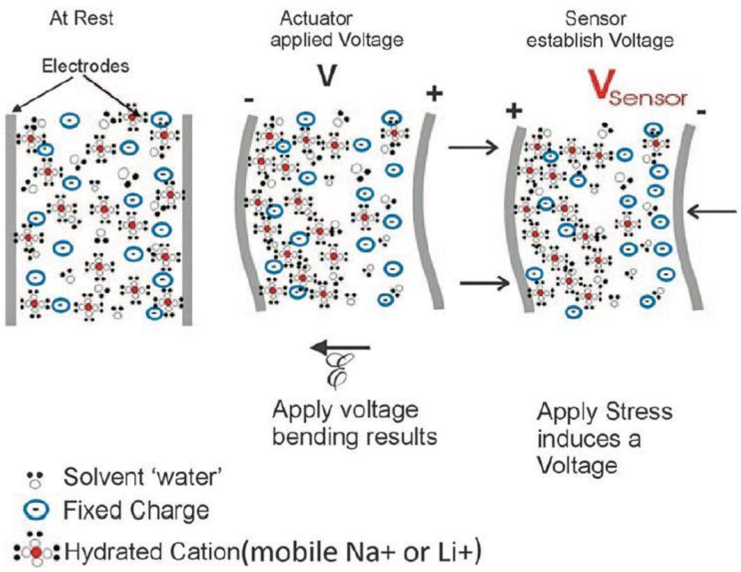


Figure 1.3: Sensing and Actuating Mechanism in IPMC (Shahinpoor, 2015)

1.2 Important of the Study

IPMC have a large potential in micro electromechanical system (MEMS) as actuator. In MEMS, actuators normally refer to capacitive type and piezo actuator. Capacitive actuator in MEMS have limited travelling distance and piezo driven actuator need high operating voltage of around 40 V. IPMC can generate large displacement at low operating voltage of 3 to 5 V but with some drawbacks. So, more study is needed so that IPMC can expand the development of actuator in MEMS field.

1.3 Problem Statement

Micropositioning stage is a platform that can move with precision of micrometer or smaller. Micropositioning stage normally used in microscope and micromirror applications. The common actuator used in this application are piezo motor or high precision stepper motor which only provide translational motion (linear motion) and rotational motion. In addition, these actuators are also expensive, require high operating voltage and are space consuming. With IPMC bending ability, it can provides tilting motion which cannot be done by other actuator. This tilting motion can provide a slanted or side view of the object that needed to be observed under microscope other than top view. IPMC also have advantages in space saving as it is as thin as paper and low operating voltage which is very useful in applying to MEMS field.

1.4 Aims and Objectives

This final year project is to study about how to fabricate a workable IPMC actuator. This project also include research about IPMC characteristics and its applications in real life.

1. To design and fabricate a IPMC actuator.
2. To study the characteristics of fabricated IPMC
3. To fabricate a IPMC micropositioner and prove its feasibility

1.5 Scope and Limitation of the Study

The scope this study on IPMC is only limited to IPMC function as actuator. This report only study about the characterises of IPMC. It is to understand how the IPMC work, response toward different voltage and study on how to integrate IPMC into application like micropositioning.

1.6 Contribution of The Study

Among the journals and papers that published about IPMC, many is about capability of IPMC, how to improve IPMC, design parameter of IPMC and only some are about applications of IPMC. Applications of IPMC mostly are applied to multi degree of freedom robot leg, micromirror, and working as sensor. So, in this project, IPMC is going to be applied to micropositioning apllication to manipulate a movement of a platform or stage using its bending capability.

1.7 Outline of the report

This report are consists of the literature review on the materials studied by other researches, methods to fabricate IPMC, methods to improve IPMC and so on. It also consists of the fabrication method used to fabricate a IPMC actuator and a IPMC micropositioner. Other than that, IPMC model was simulated using finite elements analysis. Studies on IPMC actuator capability and current voltage response were conducted to understand the characteristics of IPMC. Studies of z-axis movement and tilting movement on IPMC micropositioner also was conducted.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Studies of IPMC which are about its building material, working principles and fabrication of IPMC were reviewed. The design parameters of IPMC and the applications of IPMC were also reviewed from various sources such as journal, paper and internet.

2.2 Properties and Characteristics of IPMC

Properties of IPMC are mostly determined by the ionic polymer that used. Nafion is a type perfluorinated ionic polymer (Shahinpoor, 2015) which is classified as ionic electroactive polymer. Nafion is discovered around 1960s by Dr Walther (Shahinpoor, 2015). A typical ionic(wet) electroactive polymer have few common advantages and disadvantages. They can provides bending actuation, have large bending displacement and can operate under low voltage (Bar-Cohen and Leary, 2000).

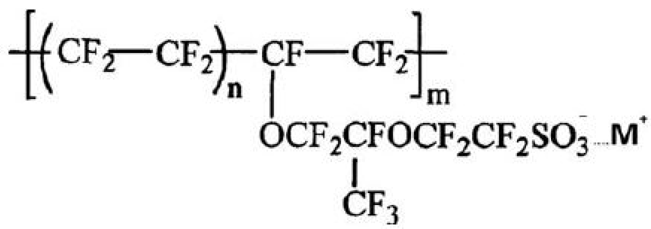


Figure 2.1: Nafion Chemical Structure with Counter Ion (Shahinpoor, 2015)

Figure 2.1 shows the structure of Nafion, where the cation M is the represent the counter ion, 'n' range from 5-11 and 'm' is ~1 (Shahinpoor, 2015). The counter ion can be hydrogen ion, lithium ion, sodium ion and so on. Nafion is a proton conductor and used in fuel cell for proton exchange membranes (Shahinpoor, 2015). Nafion has the properties of absorbing polar solvent. The polar solvent in this case is water and IPMC need water to be able to work. Water absorb by the IPMC will break the strong interaction between the sulfonate ionic group which is fixed at the polymer molecular network and the counter ions (Shahinpoor, 2015). This will lead to increase in conductivity of IPMC because the counter ions are able to move freely across the membrane (Shahinpoor, 2015).

Next, cations in the Nafion are able to move freely through the nano pores in the Nafion membrane while anion cannot (Shahinpoor, 2015). The nano pores will form when the IPMC is hydrated by solvent (normally water) due to the unique structure of the Nafion (Paquette and Kim, 2004). So, when there are voltage supply to the IPMC, the cations inside the IPMC will move or "migrate" across the membrane which follow the polarity of the voltage (Shahinpoor, 2015). This rate of moving of the cations are depends on the amount of water absorb or the conductivity of the IPMC.

On the other hand, sometimes there will be an event occurs after the voltage apply to the IPMC called back relaxation. The IPMC will revert back after bending when there are potential different across the IPMC. This is cause by the loose water or extra water that absorb by the IPMC. When voltage is supply, water will be follow and move together with the hydrated cation to the negative terminal of the electrode. When the cation settled down at the negative side, the water will move back and causes the IPMC to bend in opposite direction (Shahinpoor, 2015).

Other than that, IPMC tend to lose water when operation. This is cause by electrolyte evaporation. Since the IPMC is exposed to air with nothing to stop the evaporation of water, the water will evaporate and carry away the positive ionic charge together (Shahinpoor, 2015). This will lead to electric charge and number of electric dipoles in the IPMC to decrease and cause the conductivity reduce (Shahinpoor, 2015).

2.3 Preparation of IPMC

There are few ways to fabricate or making IPMC. The most common method to fabricate the IPMC are through electroless plating of conductor or reduction process of metal onto the surface of the ionic polymer.

The Nafion film with various thickness can be directly purchase from many fuel cell companies like Dupont. Some researcher brought Nafion resins and used hot pressing machine to prepare Nafion film with different thickness depending on the amount of resin, pressure and time to heat press (Nakamura et al., 2009).Some of the example of condition for producing different thickness of Nafion film are shown in Table 3.1. Other than that, some researcher prefer to directly coat or apply the Nafion film onto their device. They coated the Nafion film by using spin coater from Nafion dispersion solution.

Table 2.1: Conditions for Adjusting Nafion Film Thickness (Nakamura et al., 2009)

Target Thickness [μm]	200	400	800
Nafion Resin [g]	3.0	6.2	9.0
Applied Pressure [MPa]	12	10	3
Heat Press Time [min]	7	4	9
Measured Thickness [μm] (mean ± standard error)	241 ± 2.4	481 ± 9.8	1023 ± 9.7

The material selection for the electrode are depend on the conductivity and the suitability with the ionic membrane. There are two types of electrode that are normally use which are metal electrode and carbon composite electrode. For metal electrode case, there are few metal that commonly use which are Platinum, Gold, Copper, Nickel, Silver and Palladium (Shahinpoor, 2015). For carbon composite electrode, they are single wall carbon nanotube, multi-wall carbon nanotube, graphite and graphene oxide (Shahinpoor, 2015, Lee and Yoo, 2011). Platinum is a mostly use material for IPMC electrode. This is due to platinum is a biocompatible metal, MRI compatible and will not affect the CAT scans or MRI magnetic fields (Shahinpoor, 2015).

There are many processes that are involve in electroless plating method. For example, primary plating (reduction), secondary plating and ionic absorption. Here are the recipe for the electroless plating method to make the most common IPMC which is the Platinum plated Nafion IPMC (Shahinpoor, 2015): Nafion, aqueous solution of platinum ammine complex ($[Pt(NH_3)_4]Cl_2$ or $[Pt(NH_3)_6]Cl_4$), sodium borohydride ($NaBH_4$), hydrazine monohydrate (HZ), hydroxylamine hydrocholoride

(NH_2OH-HCl or HHC), dilute ammonium hydroxide solution (NH_4OH 5% solution), 30% ammonia solution (NH_3OH), polyvinyl pyrrolidone (PVP) and dilute hydrochloric acid (HCl aq, 1 N solution). The manufacturing steps of 5 cm x 5 cm size IPMC using Nafion-117 with platinum as electrode are as below (Shahinpoor, 2015, Chang and Kim, 2013, Oguro):

Pre-process of Nafion:

1) A Nafion film surfaces was roughen using 500grit sand paper (20 micron) or sand blasting. This is to increase the surface area density and to enhance the molecular diffusion.
2) The roughen Nafion film was cleaned using ultrasonic cleaning then the film was boiled in the 1 N dilute hydrochloric acid or 1.0 M sulfuric acid for 30 minutes.
3) The film was rinsed with deionised water (DI) and then boiled in DI water for 30 minutes to remove the acid and swell the Nafion membrane. Now the Nafion can be stored in DI water.

Ion Exchange (Adsorption):

1) The Nafion was immersed into the platinum salt solution. (condition: contain more than 3 mg of Pt per cm^2 of the ionic polymer's surface area, volume depend of the concentration of the Pt solution)
2) 5 ml of 30% ammonia solution (or 1ml of ammonium hydroxide) was added to neutralize or adjusting the pH value.
3) The Nafion was immersed in the solution for more than 3 hours at room temperature or one night.

Primary Plating (Reduction):

1) 5% aqueous sodium borohydride solution was prepared.
2) The Nafion with rinsed with water and placed into a 180 ml stirring water at 40$℃$.
3) 2ml of sodium borohydride was added for every 30 minutes for 7 times and in the mean time the temperature was raised to $60°C$. (add small amount of PVP as a dispersant to prevent reduced Pt nanoparticles from coalescing)

4) 20ml of sodium borohydride was added and stirred the solution for 1.5 hours at $60°C$.

5) The membrane was rinsed with DI water and immersed in dilute hydrochloric acid (0.1 N) for 1 hour.

Secondary Plating:

1) A volume of platinum complex solution was prepared for 50 cm^2 of surface area. (for each cm^2 of IPMC need 2 mg of Pt, volume depend of the concentration of the Pt solution)

2) 4 ml of 5% ammonium hydroxide solution was added to the solution.

3) 5% aqueous solution of hydroxylamine hydrochloride (HHC) and 20% solution of hydrazine monohydrate (HZ, or 20% hydrazine hydrate) were prepared.

4) The IPMC was placed into stirring Pt solution at 40 °C.

5) 6ml of the HHC and 3ml of HZ were added every 30 minutes. In the mean time, the temperature was raised and maintained at $60°C$ for 4 hours

Checking:

1) Small amount of the remaining solution was sampled and boiled with sodium borohydride using water bath.

2) Continue plating the Pt onto the IPMC with addition of HHC and HZ if the solution turn black.

3) Rinse the membrane with DI water and immerse the membrane in dilute hydrochloric acid (0.1 N) for 1 hour if the solution did not turn black.

4) The surface resistance of the IPMC was measured.

5) If the resistance not low enough repeat secondary plating.

There are alternative methods to manufacture the IPMC. The alternative methods are introduced to make the chemical process of electroless plating become more easier, cost saving and time saving (Shahinpoor, 2015, De Luca et al., 2013). Most of them, introduce new ways of coating the electrode onto Nafion membrane to replace the primary and secondary plating which have time consuming chemical reaction and involve expensive chemical (De Luca et al., 2013). Physical loaded and interlock (PLI) is one of the method which offer a way to coat the conductive material onto the surface of the ionic membrane by using hot pressing machine which replaced the ionic absorption, primary plating and secondary plating steps. These are the main recipe for PLI: Nafion membrane, Silver-based spherical powder (MOx-Doped Ag; Superior Micro-Powerder EM10500X-003A; $D_{10} < 0.8\ \mu m, D_{50} < 1.5\ \mu m, D_{90} < 2.5\ \mu m; A_{sur} < 6\ m^2 g^{-1}$) and 99% isoproply alcohol. Here are the steps to manufacture IPMC using PLI (Shahinpoor, 2015):

Material preparation:

1) Silver powder was disperse into isoproply alcohol.
2) The silver powder compound was sprayed onto the backing materials for heat press using airbrush.
3) Wait the alcohol to complete evaporate.

Hot pressing:

1) The roughen Nafion was placed in between the backing materials and facing the powder coated side.
2) Hot pressing was carried out with conditions of 2 ton at temperature of 120-130$°C$ for duration of 15 minutes.
3) The silver powder preparation and hot pressing were repeated for 3 times.

Interlock:

1) Pt powder ($D_p \sim 50\ nm$) was impregnated onto the IPMC via chemical processes to interlock the silver layer within the polymer network (De Luca et al., 2013).
2) Conductive layer (normally Gold or palladium) was electroplated on top of the interlocked electrode layer of the IPMC.

Other than PLI method, there are also researcher use other method similar to PLI. They use vacuum evaporator (Okazaki et al., 2012, Shimizu et al., 2010), e beam deposition (Chen and Tan, 2010) and sputtering coater (Siripong et al., 2005) to attach or coat the electrode on the Nafion membrane. Moreover, there are more complex manufacturing method which is for the 3D IPMC production (Shahinpoor, 2015). This method will not be included in this report as it is not used in this final year project.

2.4 IPMC Design Parameters

There are many ways to enhance the capability of a normal IPMC. The area that need to be enhance are the force generation, response speed, hydration, loss of water, repeatability, bending angle and so on. IPMC able to work under low applied potentials (Shahinpoor, 2015) which is an advantage over other type actuator like shape memory alloy. In order to make the IPMC applicable in real life, many researcher doing research about how to improve IPMC.

2.4.1 Cation in IPMC

First and foremost, by introducing different type of cation in IPMC can enable IPMC varies the magnitude of force. Introducing lithium ions into IPMC can allow IPMC to produce maximum force follow by sodium ion, potassium ion and so on (Shahinpoor, 2015). In Figure 3.2 shown the force generate against type of cation introduced.

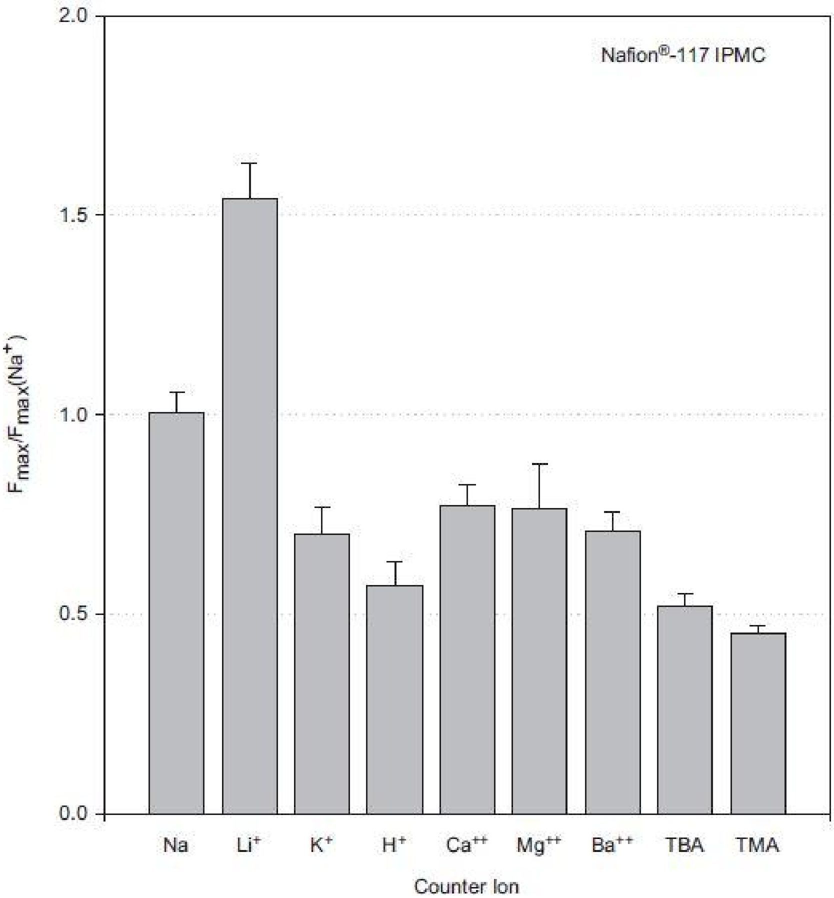


Figure 2.2: Bar Chart of Force Generated by Different Cation in IPMC. The Results are Comparison Made against Sodium Ion in term of Maximum Force Generated at 0 Displacement (Shahinpoor, 2015).

2.4.2 Water/ hydrolysis/Ionic liquid in IPMC

Next, IPMC have problem of losing water when large voltage is applied or during actuation operation. The IPMC fail to perform when loss too much water in an actuation operation as an actuator. To account for this problem, there are two ways. One of the ways is encapsulation (Shahinpoor, 2015, Lei et al., 2014). This method is to coat a layer of material to prevent the loss of water through air or through surrounding. Parylene C is an effective material for encapsulation to minimize the water leakage from IPMC (Lei et al., 2014). This is because parylene C have very low water vapour transmission rate, low Young's modulus of 0.4MPa and it can be coated uniformly and pinhole free on the surface of IPMC by using chemical vapour deposition system (Lei et al., 2014). In Hong Lei and others' research on encapsulation of IPMC, the parylene are coated using a parylene coater (PDS2035) under low pressure of 30 mTorr and use plasma treatment to improve the adhesion between parylene and the platinum electrode. Another way of minimize the hydration is to use ionic liquid. Ionic liquid are use to replace water inside of IPMC so that IPMC can work for long period of time regardless of the atmospheric humidity (Okazaki et al., 2014). In Hiroshi Okazaki research on soft actuator IPMC driven using ionic liquid, 1-ethyl-3-methyl-imidazoliumtetrafluroborate is used as the ionic liquid (EMIBF4). The ionic liquid is introduced to the IPMC by several steps. The steps start with mixing the ionic liquid with water and heated to $90°C$. The IPMC is then soaked into the ionic solution for 30 minutes. The IPMC driven using ionic liquid shows promising result. The comparison between IPMC driven using water and driven using ionic liquid are shown in Figure 3.1 and Figure 3.2 (Okazaki et al., 2014).

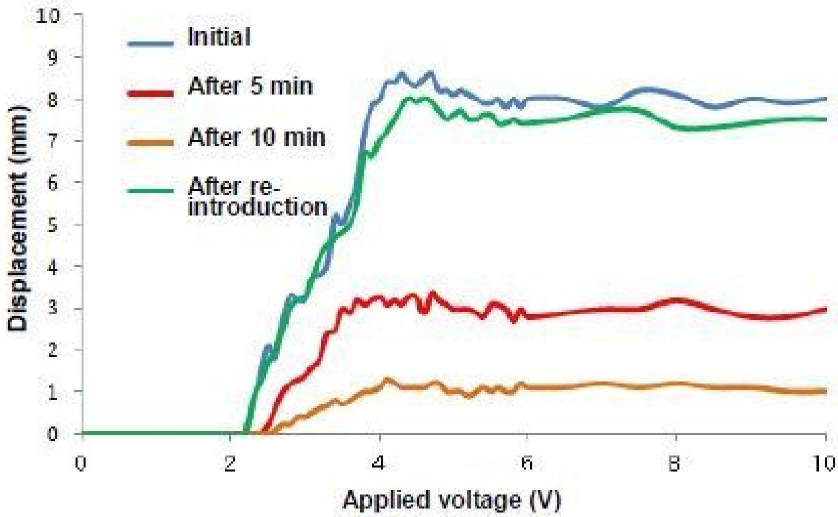


Figure 2.3: Graph of Displacement against Voltage for IPMC Driven using Water (Okazaki et al., 2014)

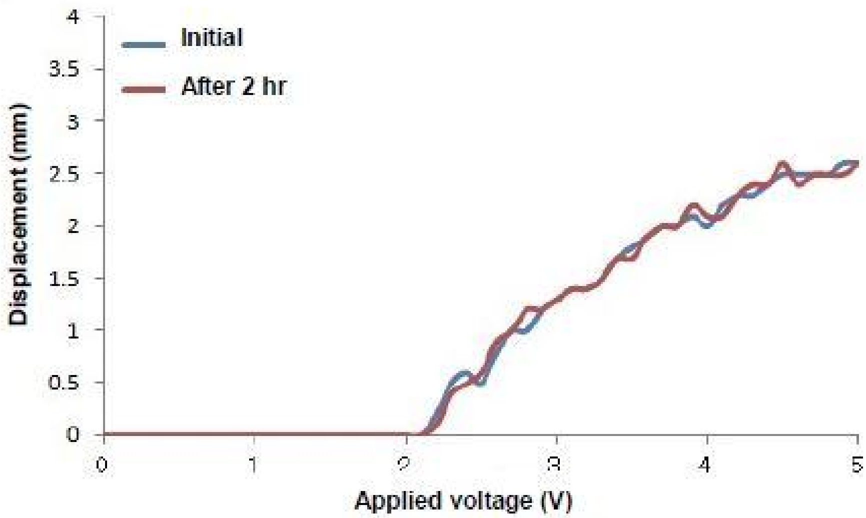


Figure 2.4: Graph of Displacement against Voltage for IPMC Driven using Ionic Liquid (Okazaki et al., 2014)

In addition, IPMC has a slow actuation response or slow reaction. There are some research about doping or mixing other material into Nafion polymer like graphite oxide (Lian et al., 2010). For example in Kan Bian, Hongguang Liu and others research on enhancing IPMC actuation response, they dope electroactive barium titanate nanocomposite, BaTiO3 into the Nafion membrane (Bian et al., 2016). Basically, barium titanate enhance IPMC's mechanical and electromechanical properties of Nafion-based IPMC membranes. Other than enhance the response, doping barium titanate nanocomposite increase IPMC conductivity, have better capacitance, better Young's modulus and tensile strength (Bian et al., 2016). The recipe needed for creating a $BaTiO_3$/Nafion composite are barium titanate nano powder, 25% Nafion solution and Dimethyl sulfoxide (DMSO).

With the steps to prepare barium titanate and Nafion nanocomposite which recast the ionic polymer membrane (Bian et al., 2016):

1. 25% Nafion solution was prepared at $50°C$ in a vacuum.
2. DMSO and Nafion solution were mixed with ratio of 1:40.
3. The bubbles in the mixture solution were removed by using ultrasonic irradiation for 20 minutes.
4. The mixture solution with barium titanate nanoparticles were mixed with desired mass ratio (100:1, 100:3, or 100:5).

5. The $BaTiO_3$/Nafion composite was irradiated using an ultrasound with frequency and power of 40 kHz and 900 W for 2 hours.
6. The composite was kept in an oven at $60\,°C$ for 10 hours and the composite was heated at $100\,°C$ for 3.5 hours to form a uniform membrane.

2.4.3 Strength

Moreover, to increase the tip strength and displacement travel by IPMC, the ionic polymer thickness have to be thick. This is because the force generated is determine by the bending stiffness and the thickness of ionic polymer film. To fabricate a thick IPMC needs a good control over the process variables like temperature and concentration of solvent used. In Sang Jun Lee and others research on new fabrication method for IPMC actuator and application, they use hot pressing machine to hot press few thin film of Nafion together.

The step to produce Nafion stacks for thick IPMC (Sang Jun et al., 2006):

1. Few Nafion films were prepared and adjusted with proper dimension.
2. The Nafion films were rinsed with acetone.
3. The Nafion films were stacked in steel mold with polyimide film.
4. The Nafion films were hot pressed with the mold at $180\,°C$ without pressure for 20 minutes and then hot pressed with 50 MPA at $180\,°C$ for 10 minutes.
5. The Nafion stacks were let to cool down to room temperature and proceed to cleaning the Nafion and coating of electrode.

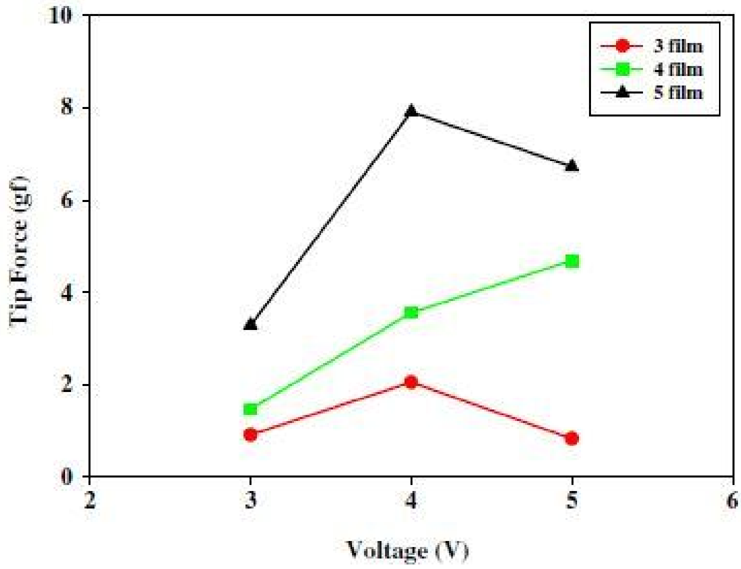


Figure 2.5: Tip Force of IPMC against The Stack Number/Thickness of IPMC (Sang Jun et al., 2006)

2.5 Microactuator applications

IPMC is a composites that can act as sensors and actuator. IPMC deform when electric field is applied and electric signal is produce when the IPMC is deformed. This characteristic also enable IPMC act as an transducer like self-sensing IPMC. Self-sensing IPMC is a device where a least 3 IPMC strip stack together as an actuator with feedback control (Kruusamäe et al., 2015).

IPMC actuator is a non-linear system. It is affected by many factors which are driving signal, size of the IPMC film, surface resistance of the IPMC and the amount of water in the IPMC (Chang and Kim, 2013). First, the bending motion will be larger when the driving voltage is increased but it will damage or burn the electrode of the IPMC when the voltage supplied is too high (~10 V) (Chang and Kim, 2013). Secondly, the thickness of the IPMC affects the bending of IPMC as well (Chang and Kim, 2013). The thicker the IPMC strip, the higher the stiffness of the IPMC. So, the force generate are higher as well but the deflection of IPMC will be smaller and slower. Thirdly, the bending also being affected by the conductivity of the electrode (Chang and Kim, 2013). When there are no power loss at the electrode of IPMC due to the surface resistance, thus the IPMC is said to be in highest efficiency. The surface resistance is controlled by the thickness of the electrode. In order to achieve a very low surface resistance, the thickness of electrode have to be controlled during the fabrication of IPMC. Lastly, water is essential for IPMC (Chang and Kim, 2013), as too less water will have decrease the conductivity of the ionic membrane. On the other hand, existence of too many water molecules will swell the IPMC and cause the increase the surface and internal resistance. So, the concentration of the water in IPMC have to in the right amount to give the best outcome.

Nafion-based IPMCs have large potential in many applications and many industrials. For example, IPMC can be used for biomedical, robotics and space applications. IPMC can be used in making a micro gripper (Shahinpoor et al., 1998, Shahinpoor, 2015), micro pump (Wang et al., 2014), legs for mini robots (Chang and Kim, 2013), fins and propulsion for aquatic robot (Aureli et al., 2010, Kwok et al., 2001), lens with variable focal length (Shimizu et al., 2009), refreshable Braille display (Feng and Hou, 2015), artificial fingers (Sang Jun et al., 2006) and so on. In robotics application, IPMC actuator are use to change the direction of the robot or act as the propulsion like tadpole tail especially as the fins in the fish robot and in aquatic robot. Other than that, in robotics arm and gripper application, IPMCs are used to control the fingers of robotics hand or arms of the gripper. In refreshable Braille display case, IPMCs are used to control the lifting or dropping of the 'dots' of the Braille code for blind people to read. IPMC is the micro pump are use to change the pressure inside a chamber or reservoir to pump the fluid in the chamber out.

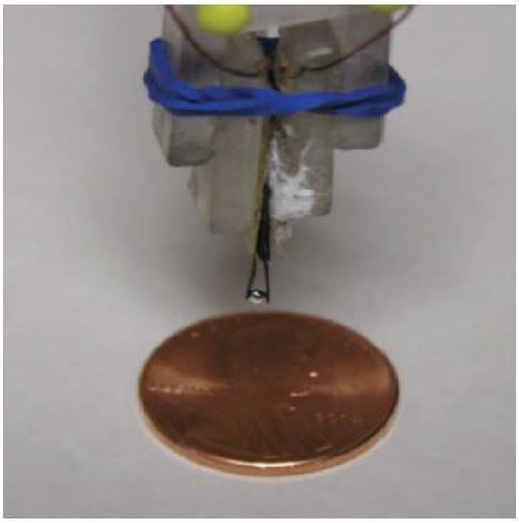
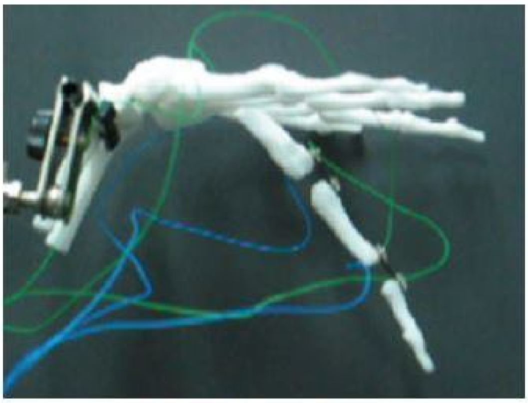
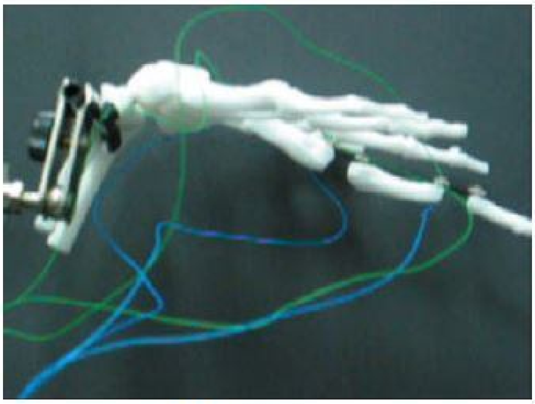


Figure 2.6: IPMC as Micro Gripper (Shahinpoor, 2015)



(a) initial state



(b) up-motion

Figure 2.7: IPMC as Artificial Muscle (Sang Jun et al., 2006)

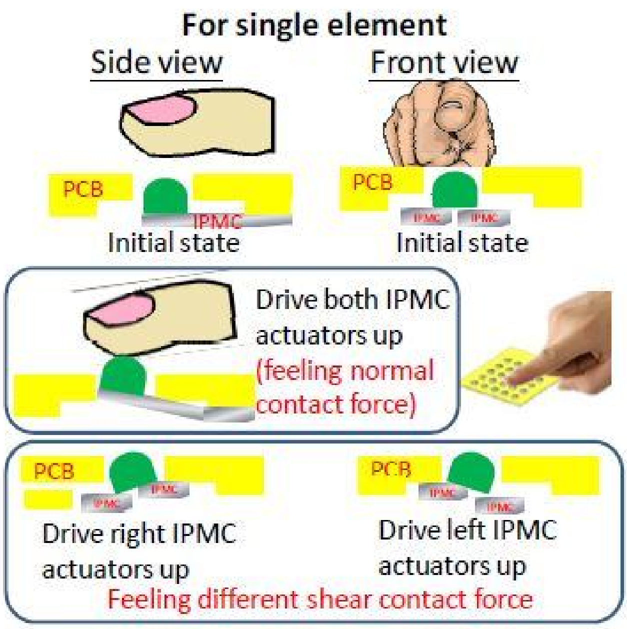


Figure 2.8: IPMC as a Braille Code Actuator (Feng and Hou, 2015)

Moreover, by make use of the characteristic of IPMC that IPMC able to generate electric signal as sensors, IPMC can be used in energy harvesting device. The IPMC convert the kinetic energy from the waves to electrical energy. Although there are some problem needed to be solve for this energy harvesting module using IPMC, but the result are very good (Park et al., 2014). IPMC also used as Proton Exchange Membrane (PEM) in fuel cell to change chemical energy to electrical energy (Hawut et al., 2006).

2.6 Summary

Bending motion of IPMC is depends on the transfer of water and ions molecules inside the ionic membrane. Common ways to fabricate a IPMC is through chemical plating. There are many design parameters to improve the capability of fabricated IPMC. For example, introduce new ions into the ionic membrane like lithium or sodium. IPMC also being apply in applications like artificial muscle, aquatic robot actuator, Braille code actuator and so on.

CHAPTER 3

METHODOLOGY

3.1 Introduction to Fabrication of IPMC

The materials involve in the fabrication are: nafion (ionic polymer) and silver (electrodes). The silver-based IPMC was fabricated using silver mirror method. The fabrication methods were divided into three stages, namely pre-processing of ionic membrane, chemical electrode plating (or coating) on the surfaces of the ionic membrane and electrode thickening of the electrode. Then post-processing of IPMC.

3.2 Simulation

In order to visualize the response of the IPMC in bending motion, a finite elements analysis model was simulated using Multiphysics COMSOL software. Through finite elements analysis, von Mises stress and the displacement of the IPMC strip can be visualize when apply with 5 V sinusoidal wave.

The variables for the simulation of finite elements analysis are set by referring to value set in other journal papers (Ruiz, 2013, Pugal et al., 2015). Some of the parameters and variables used in the simulation is shown in Table 3.1.

Table 3.1: Parameters and Variables used in Simulation (Pugal et al., 2015).

Name	Unit	Description
Constant value		
F	96485.3415 [s*A/mol]	Faraday Constant
epsilon	2 [mF/m]	Dielectric permittivity
Conc_cat_mol	1200 [mol/m^3]	Cation concentration
D_cat	7e-11 [m^2/s]	Diffusion constant
alpha	0.0001 [N/C]	Linear force coupling
T	293.0 [K]	Temperature
Young_IPMC	41 [MPa]	Polymer Young modulus
Poisson_IPMC	0.49	Polymer poisson constant
Variables		
V_pos	5*sin((2*pi[rad/s])*t)	Voltage at positive electrode
V_neg	0	Voltage at negative electrode

By referring to 2D model IPMC in Pugal et al's Modeling Ionic Polymer Metal Composites with COMSOL, 3D model of IPMC was simulated by applying with same parameters and variables (Pugal et al., 2015). The mesh and number of elements in a surface and across volume was reassigned to accommodate the volume needed in 3D geometry.

3.3 Fabrication of IPMC

3.3.1 Pre-processing of IPMC

Before performing the silver plating, the nafion was cleaned using hydrogen peroxide, H_2O_2 and sulphuric acid, H_2SO_4. This process is to remove the organic impurities from the nafion membrane. This cleaning process take around six hours, involving the chemicals: 3 volume % of H_2O_2 solution and 0.5 mol/L of H_2SO_4. The following procedure shows the cleaning of nafion membrane:

1. 3 v % of H2O2 solution was prepared in a beaker. The volume of H2O2 must be able to fully submersed the Nafion film.
2. The temperature of H2O2 solution was heat up until 80 °C and maintained at 80 °C.
3. Nafion membrane was immersed into the solution for an hour.

4. The solution was stirred constantly using glass rod during this one hour to remove the bubbles formed on the surface of the Nafion.
5. Same volume of DI water as the H_2O_2 was prepared and the temperature was increased and maintained at 80 ℃.
6. Nafion membrane was immersed into the DI water and stirred constantly for an hour.
7. 0.5 mol/L of H_2SO_4 solution was prepared.
8. The temperature of H_2SO_4 solution was increased and maintained at 80 ℃.
9. Nafion membrane was immersed into the H_2SO_4 solution for an hour and stirred using glass rod to remove bubbles.
10. Treated Nafion membrane was immersed into DI water at 80 ℃ for an hour and stirred using glass rod to remove the bubbles.
11. Treated Nafion membrane was rinsed 2-3 times with DI water.
12. The treated Nafion membrane was stored in DI water.

3.3.2 Silver Mirror Method

The silver mirror method was used to coat the IPMC with electrodes. This method is similar to Tollen's test which is also called silver mirror reaction (Katz, 1997). The chemicals needed in silver mirroring method are D+ glucose, silver nitrite, 28 w% ammonia solution and sodium hydroxide. Two solutions will be made using these 4 chemicals. The first solution is made using silver nitrate and ammonia solution. The second solution is made using D+ glucose and sodium hydroxide. Let the first solution be solution A and the second solution be solution B. Here are the steps to plate the silver onto the surface of the nafion membrane.

1. 1.2 g of silver nitrate and 60 g of water were prepared. Both silver nitrate and water were mixed to form 1.96 w% silver nitrate solution.
2. 2 g of 28 w% ammonia solution was added into the silver nitrate to obtain solution A.
3. 1.6 g of sodium hydroxide and 60 g of water were prepared. Both sodium hydroxide and water were mixed to form 2.597 w% of sodium hydroxide solution.
4. 0.8 g of D+ glucose was added into sodium hydroxide solution to get solution B.

5. The cleaned nafion membrane was immersed into solution A for 15-30 minutes. Flipping the nafion membrane constantly.
6. The nafion membrane was dipped into solution B until no black cloud is observe. Flipping the nafion membrane gently during this interval to ensure silver form on both side of the nafion membrane.
7. The IPMC was dried. Step 5 and step 6 were repeated to increase the thickness of silver electrode.
8. The edges of IPMC were cut to ensure no connectivity between top and bottom electrode.
9. The fabricated IPMC were stored in DI water.

3.3.3 Post-processing of IPMC

This process is to introduce new cations into the nafion membrane to enchance the displacement of IPMC can be maximize. Lithium ions was introduced into the IPMC by immersing the IPMC into 1 M of lithium chloride solution. Steps to prepare the 500 ml of 1 M lithium chloride solution were shown below:

1. 21.2 g of lithium chloride and 478.8 ml of DI water were prepared.
2. Both lithium chloride and water were mixed together to form lithium chloride solution.
3. IPMC membrane was immersed into lithium chloride solution for 12 hours to 1 day.
4. The IPMC was stored in DI water.

3.4 Fabrication of IPMC Device

The micropositioning stage perform up and down movement (z-axis movement), and tilting movemen. The design of the IPMC device was drew using autoCAD software. The micropositioning stage consists of 4 legs and a measurement stage. Figure 3.1 shows the layout of the 4 IPMCs legs (indicates as darkened areas).

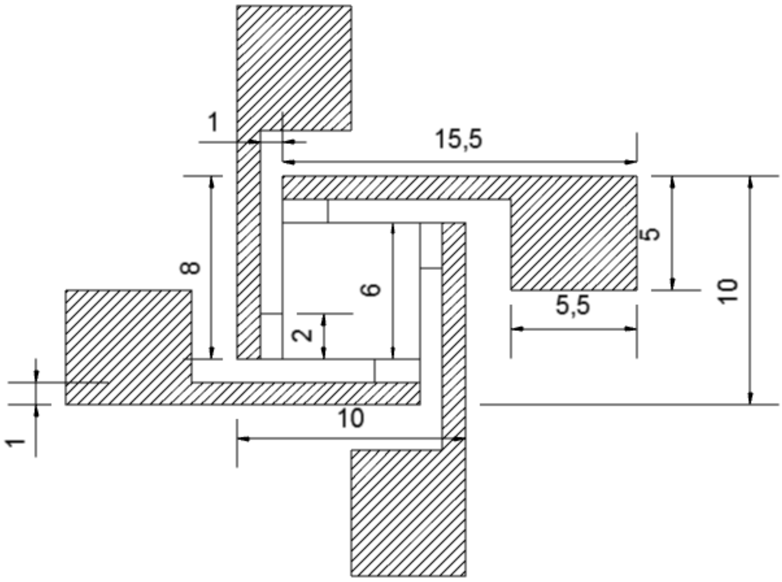


Figure 3.1: IPMC Micropositioner with Dimension in mm.

This micropositioner was monolithically fabricated at the nafion. The IPMC was directly fabricated onto micropositioner by coating silver onto the legs of the micropositioner. A hard material like aluminium piece will be paste at the square middle part to act as the stage.

The fabrication of the micropositioner was started by creating pattern on top of the nafion membrane surface using photolithography. This is to cover the nafion from silver coating. The photoresist used for creating the pattern is negative type photoresist where the area did not expose to UV ray can be washed away by using potassium hydroxide solution. A mask was designed with the micropositioner pattern. The silver coated area shown in Figure 3.2 with the shaded region.

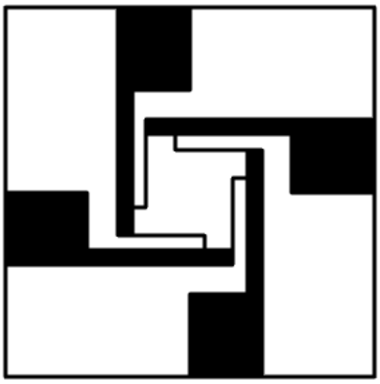


Figure 3.2: Mask of Micropositioner for the Negative Photoresist

Before silver mirror process, a protective layer was adhered on top of the photoresist. This is because photoresist is weak against alkali and acid which are the ammonia and sodium hydroxide used in the silver mirror method. Since the nafion membrane is transparent, only one side of the nafion was laminated with photoresist. The pattern formed using photolithography can be seen from both side of the membrane, so protective layer with pattern can be added to both surfaces of the nafion and only expose the plating area. Lastly, the unwanted part was removed after silver mirror process and the fabrication of IPMC micropositioner was completed. The overview of the whole process is shown in Figure 3.3 which is drawn using SolidWork.

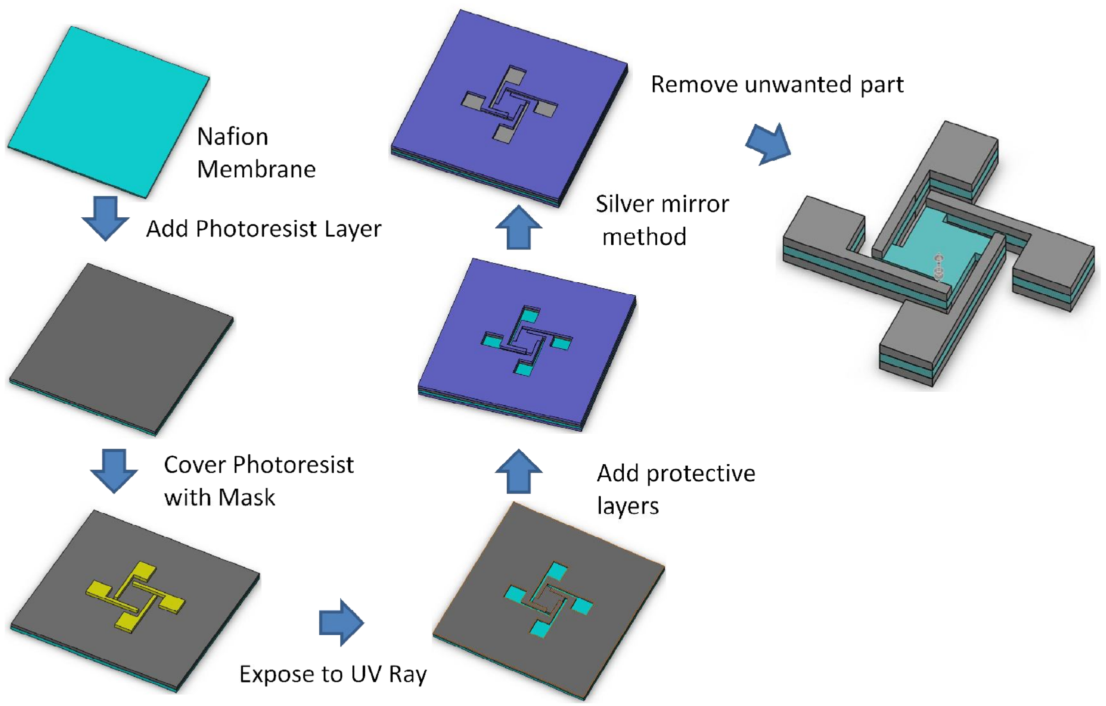


Figure 3.3: Fabrication of IPMC Micropositioner Steps by Steps.

3.5 Structure of IPMC Observed Under SEM

A cross section view of a sample of fabricated IPMC were observed under Scanning Electron Microscope (SEM) and shown in Figure 3.4. From Figure 3.4, the fabricated IPMC have ~153μm of nafion layer, ~12.6μm of silver layer on the top of nafion and ~6.61μm of silver layer at the bottom of the nafion.

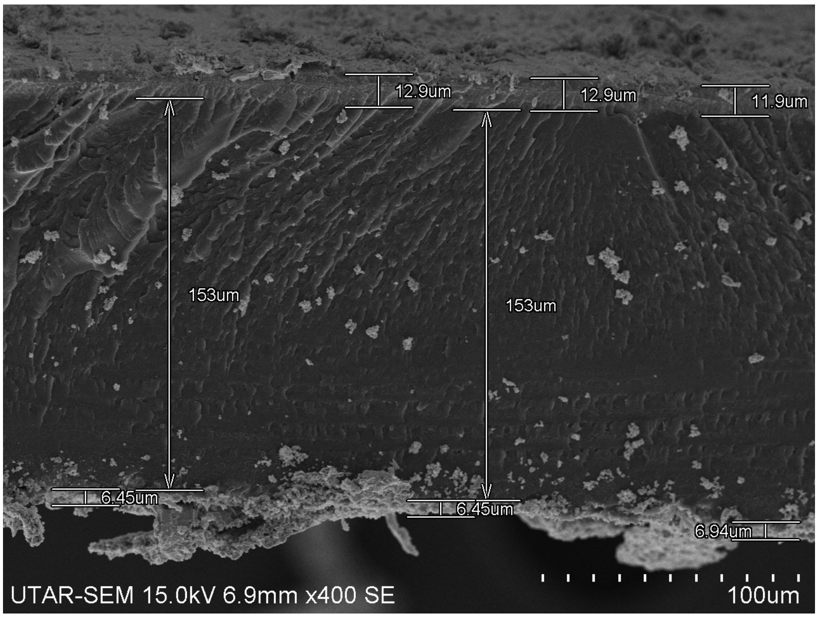


Figure 3.4: Cross Section View of IPMC

3.6 Experiment Setup

To use IPMC as an actuator, the characteristics of IPMC was determined. First, the fabricated IPMC must have the ability to bend when a voltage is applied to lift up or tilt an object. Hence, range of operating voltage to achieve deflection was studied and repeatability of the actuator was evaluated.

Other than mechanical study, when a constant DC voltage is apply to the IPMC beam actuator, the beam will bend and the current across the IPMC will gradually drop over period of time. After a while, the IPMC will eventually stop moving when the current drop are low. This shows that the current characteristics of IPMC when different voltage is supplied.

3.6.1 Voltage Current Response

To study current response of the device, the measuring device was connected in series with a fixed resistance and calculate current from the voltage across the fixed resistance.

A 1 ohm resistor was connected in series with the IPMC and the voltage changes can be observed through the oscilloscope. Since the resistor is 1 ohm, the voltage changes observed is also equal to the current changes. Each IPMC strip is fixed with dimension of 2 cm x 1 mm.

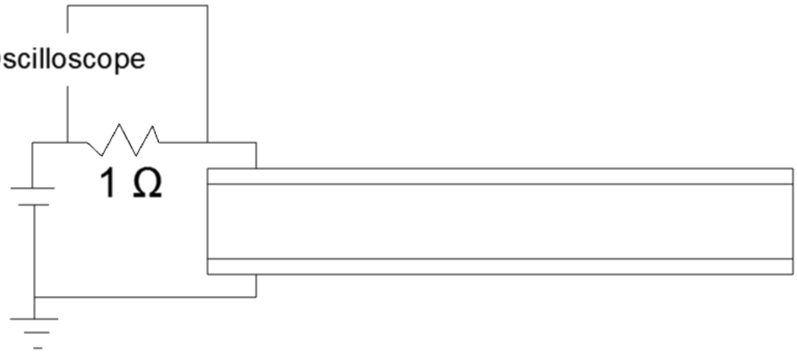


Figure 3.5: Experiment Setup to Detect the Voltage Current Response.

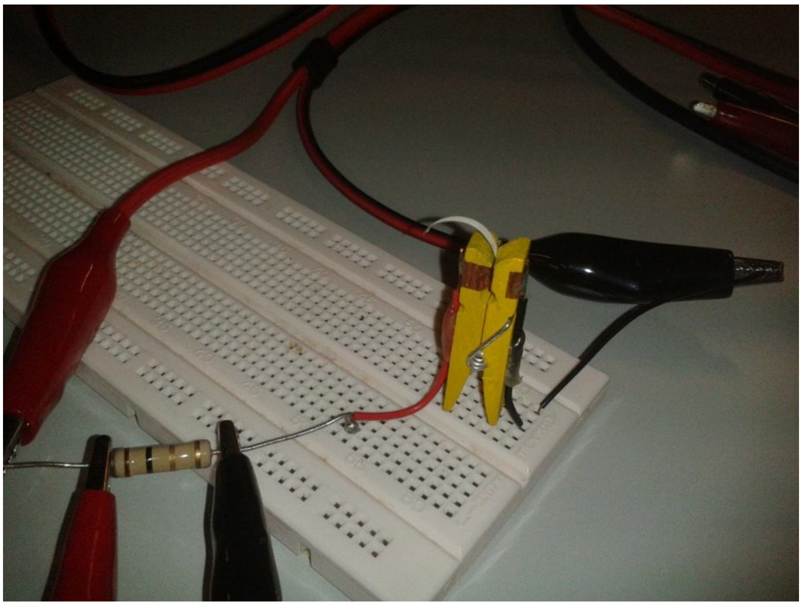


Figure 3.6: Experiment Setup for Current Voltage Response.

3.6.2 Single Strip IPMC Bending Displacement

To control a strip of IPMC to move a distance, the relationship between voltage and displacement have to be studied. A 2 cm x 1 mm strip of IPMC is supplied with different voltage level and the distance travel will be recorded using laser displacement sensor.

The experiment setup is same as experiment setup in Figure 3.5 which is also shown in Figure 3.7 but there is no oscillator and with laser displacement sensor measuring the displacement at the tip of the IPMC. The tip of the IPMC in Figure 3.7 bend out the range of the laser sensor spot (circled in red).

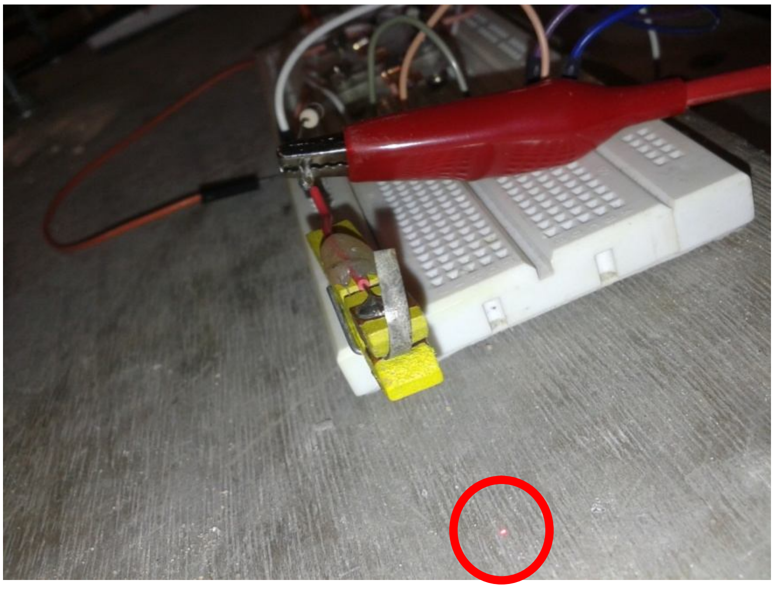


Figure 3.7: Experiment Setup for Bending Displacement.

3.6.3 Movement of Micropositioner

Silver based IPMC microstage will move up or down when 4 legs are having the same voltage with same direction. The stage is clamped with custom made clamp and put under a laser displacement sensor. The pointer of laser is point to the centre of the stage to detect the displacement.

For tilting movement of the stage, 2 legs which are side by side have to be activated with voltage in same direction and magnitude. The laser spot will be place at the side of the stage that have maximum displacement. Then use Trigonometry to find the tilt angle of the stage.

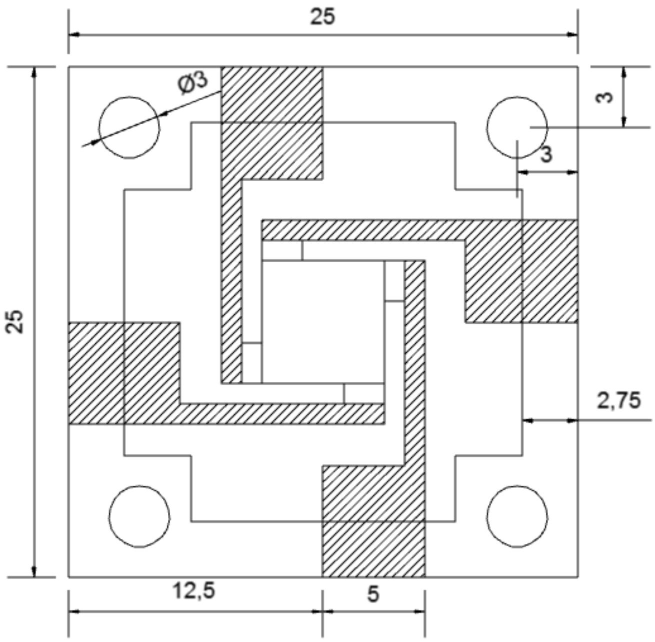


Figure 3.8: Micropositioner with Clamp in AutoCAD Drawing (Top View)

3.7 Summary

The IPMC that is fabricated and used in this final year report is silver-based nafion IPMC. Silver based IPMC can be fabricated using silver mirror method. With the photolithography and addition protective layer, IPMC integrated micropositioner can be fabricated. Simulation using finite elements analysis shows the distribution of von Mises stress and displacement travel by each segment of the IPMC. This also help to design in designing the clamp of for the IPMC micropositioner as prevent the clamp from disturbing the bending motion of the IPMC in the device.

Few experiments were done to take data and results. The voltage current response of IPMC and displacement travel by IPMC can be taken by supplying voltage to the 2 cm x 1 mm IPMC strip and recorded through oscilloscope and laser displacement sensor respectively. The z axis movement of the IPMC micropositioner can be measured using laser displacement sensor with 5 V supplied to all of the legs of the micropositioner. While for tilting angle, with 5 V supplied to 2 consecutive legs, the stage will be tilted with certain angle.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

Results have been taken from simulation of IPMC using COMSOL, current voltage response of IPMC, experiments to study the displacement of IPMC with different voltage, and study on performance of IPMC micropositioner in z-axis movement and tilting movement.

4.2 Simulation

Simulation of deflection of IPMC strip and the von Mises stress were done by using Multiphysics COMSOL software. A 3D model of IPMC were drawn using COMSOL and shown in Figure 4.1. The small portion on the left (circled in red) is the clamped part and the area where voltage is supplied.

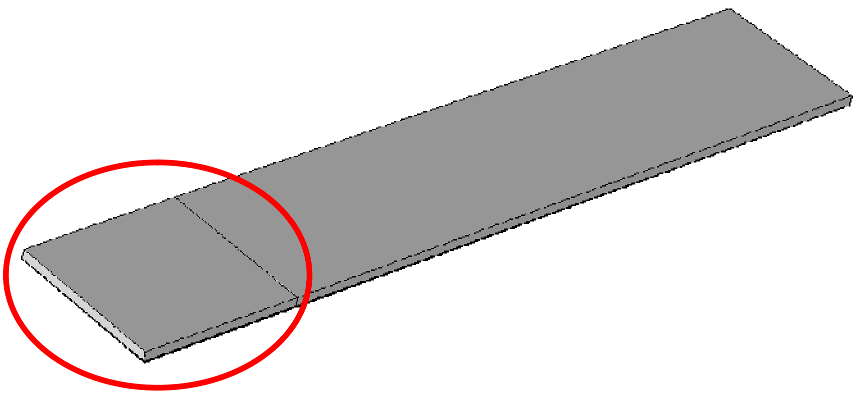


Figure 4.1: 3d Model of IPMC in COMSOL.

To start simulating using this 3D IPMC model, all parameters and variable were assigned to the boundaries, surfaces and mechanical properties of IPMC. Meshes and elements were assigned to the IPMC model by dividing the whole model into small pieces (Shown in Figure 4.2 and Figure 4.3).

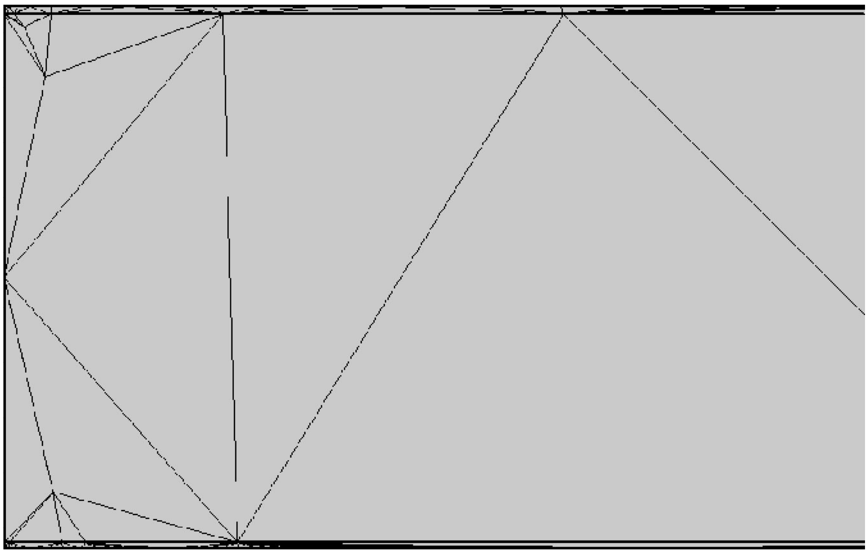


Figure 4.2: Meshes of the IPMC Model View from Side View

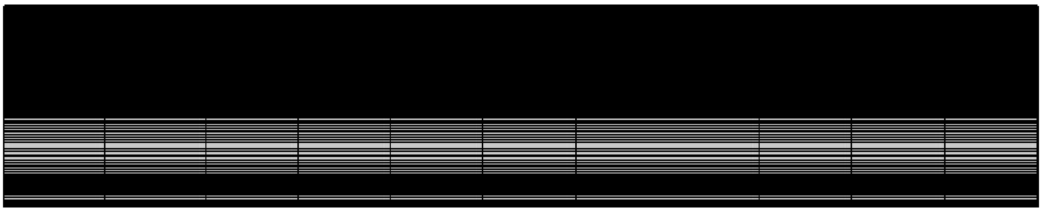


Figure 4.3: Meshes of IPMC Model View from Top View

The distribution of displacement and von Mises stress in each element inside the IPMC strip were shown in Figure 4.4 and Figure 4.5. The von Mises stress shown the deformation of the IPMC when supplied with 5 V mostly concentrated right after clamp region of the IPMC. On the other hand, maximum displacement was observed at the end tip of the IPMC.

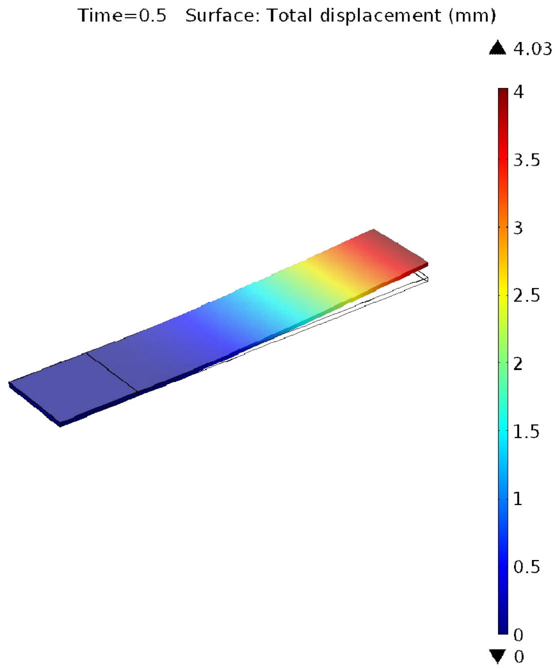


Figure 4.4: Simulated Displacement of the IPMC with Colour Legend

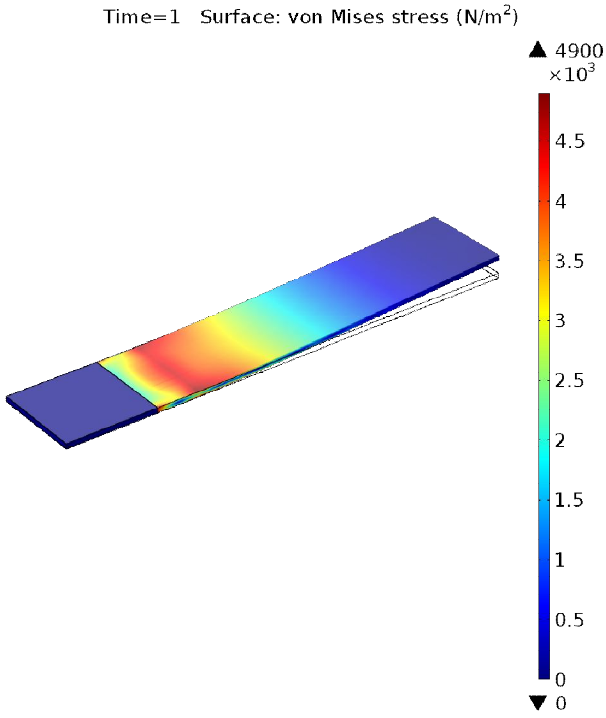


Figure 4.5: Simulated von Mises Stress in IPMC with Colour Legend.

4.3 Current Voltage Response

A 2 cm x 1 mm IPMC strip was connected with 1 ohm resistor in series. This circuit was supplied with 1 V, 3 V and 5 V. The voltage response across the 1 ohm resistor is also equal to current response of the IPMC taken using digital oscilloscope.

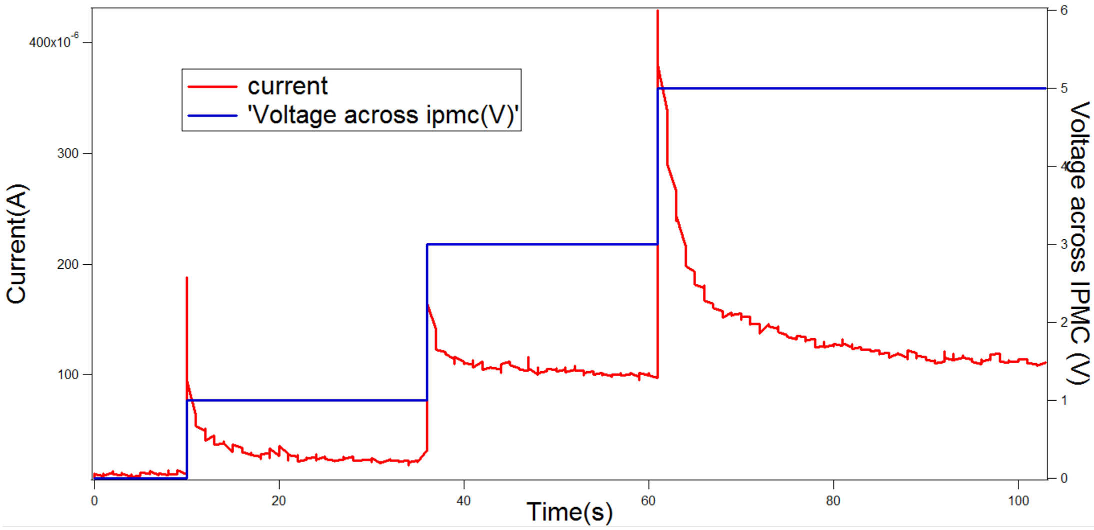


Figure 4.6: Graph of Current Response of IPMC with Different Voltage Across Time

When 1 V step voltage was supplied to the IPMC, the current spike up and drop to a steady state level. The trend are similar to 3 V and 5 V. The higher the step voltage the higher the current steady state level. The current flow across the circuit is in range of 0 A to 0.4 mA. From the current response, we can calculate the resistance of the IPMC using Ohm's Law. The resistance across the IPMC is high ($\sim 10\ k\Omega$ at peak of current for each voltage) and changes across time until the resistance reach steady state. This may be related to the ions transfer rate in the nafion membrane.

4.4 Single Strip IPMC displacement

Displacement travel at the tip of the IPMC strip was studied using laser displacement sensor at different supplied voltage. Figure 4.7 depicts the temporal response of the IPMC strip. In this figure, there is a sudden drop in displacement. This is due to the maximum detectable range by the laser sensor, the IPMC bend up and move out of the range of the laser spot. To have a fair comparison between displacement for different voltage, the displacement of the IPMC tip were compare between time 0 second to 2 seconds after step voltage is supplied.

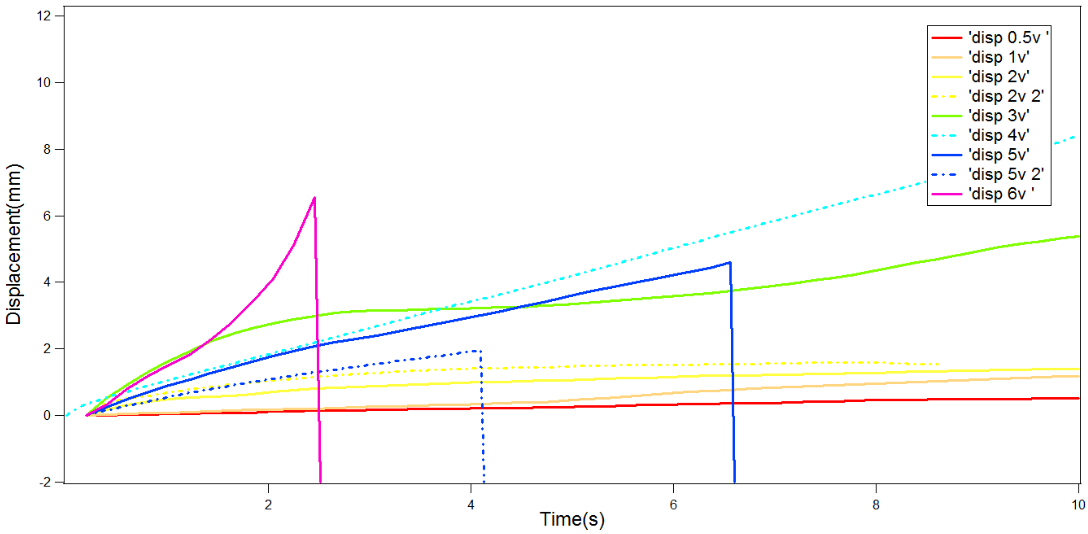


Figure 4.7: Graph of Displacement of IPMC for Different Voltages Across Time

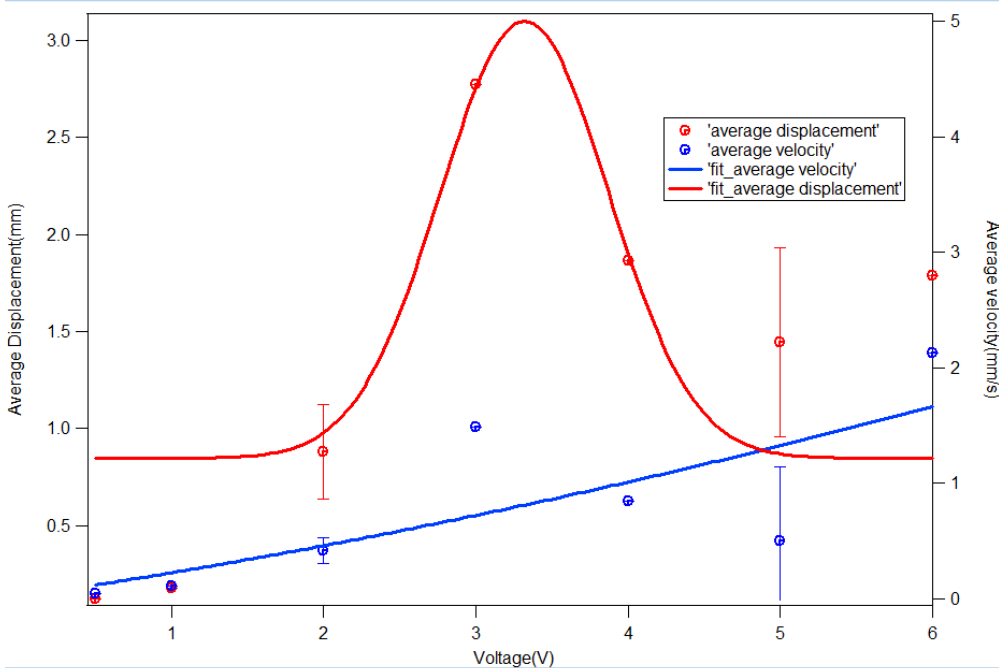


Figure 4.8: Graph of Average Displacement and Average Velocity at 2 s with Different Voltages

In this experiment, the voltage is set to be 0.5 V, 1 V, 2 V, 3 V, 4 V, 5 V and 6 V. Displacement, voltage and time are independent from each other. From Figure 4.7, the distances travel by tip of IPMC were increase linearly across the time for different voltages. When the voltage increases, the average displacement also increases. This can be seen from Figure 4.8 where displacement at 2 seconds were compared for different voltages. But the displacement at 2 s drop when the voltage is at 4 V and 5 V. At 6 V, the displacement is increase by higher than displacement at 5 V. A best fit curve was drawn using gauss function. From the curve, the highest average displacement is at around 3 V.

The velocity of the tip of the IPMC can be calculated by finding the gradient of the distance time line. By drawing best fit lines for each distance-time curve, the gradient or velocity of the tip can be calculated. From the best fit line in Figure 4.8, the average velocity shown is increased with the increased in voltage supplied.

This results shows that, the optimum operating voltage is around 3 V to 4 V. But the 5 V is selected as the operating voltage for IPMC micropositioner. This is because most electronics device is operated in 5 V range. The displacement and velocity shown in the Figure 4.8 for 5 V are also close to average displacement and velocity for 3 V and 4 V.

4.5 Up and Down Movement of IPMC Micropositioner

2 IPMC micropositioner were use to taken z- axis movement of the micropositioner which measured and recorded using laser displacement sensor in Figure 4.10 and Figure 4.11. In Figure 4.9 shown the micropositioner move down when -5 V was supplied to 4 legs of the IPMC. Since each IPMC have slightly difference in bending distance, the stage was slated a bit (circled in red).

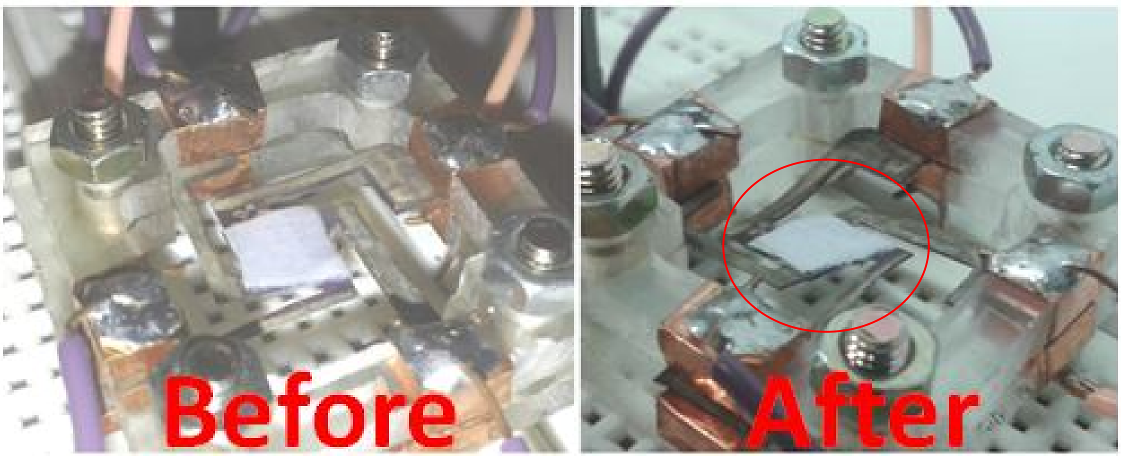


Figure 4.9: Down Movement of the Micropositioner under 5 V.

In Figure 4.10, the IPMC was supplied with step voltage of 5 V for 15 s. The displacement of the stage is increase exponentially until it reaches steady state. This IPMC micropositioner shows a maximum of ~1.2 mm displacement in upward movement and around ~1.1 mm for downward movement. While for second IPMC micropositioner, it gave a maximum 1.1 mm displacement for downward movement and displacement of around 0.8 mm for upward movement (shown in Figure 4.11). When there is voltage supply was turn off at 15 s for Figure 4.10 and at 34 s for Figure 4.11, the IPMC legs show a decrease in distance. This is maybe due to the concentration of water and ions molecule in the IPMC tries to move to other side of the electrode to balance the concentration.

This results show that, IPMC can be integrated into micropositioner to perform upward and downward movement in micro scale. IPMC micropositioner that fabricated successfully achieved average of 1 mm of displacement for up and down movement.

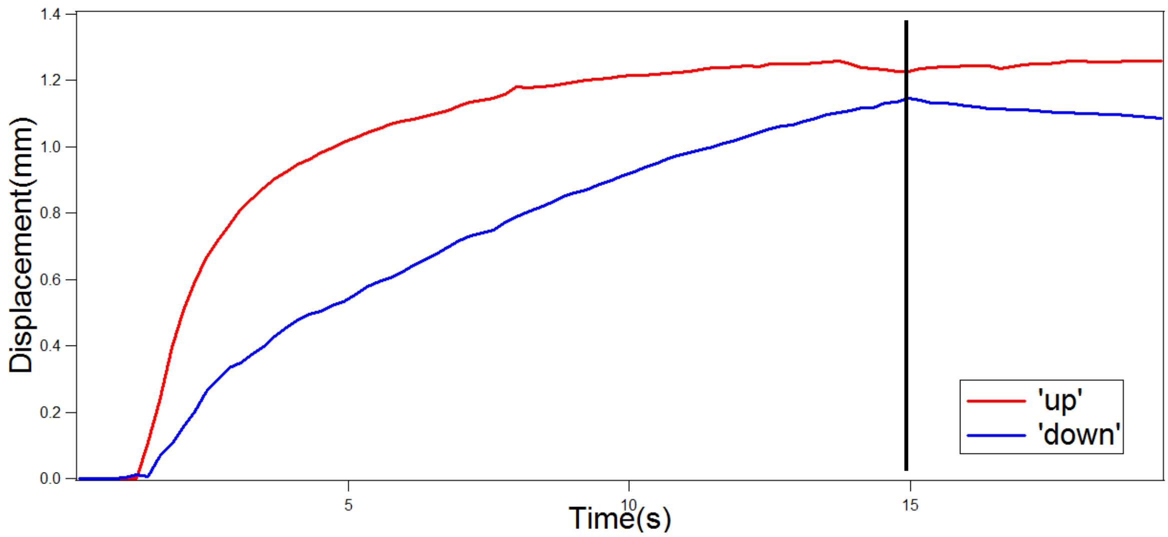


Figure 4.10: Graph of Displacement of the IPMC Micropositioner 1 along Z-axis

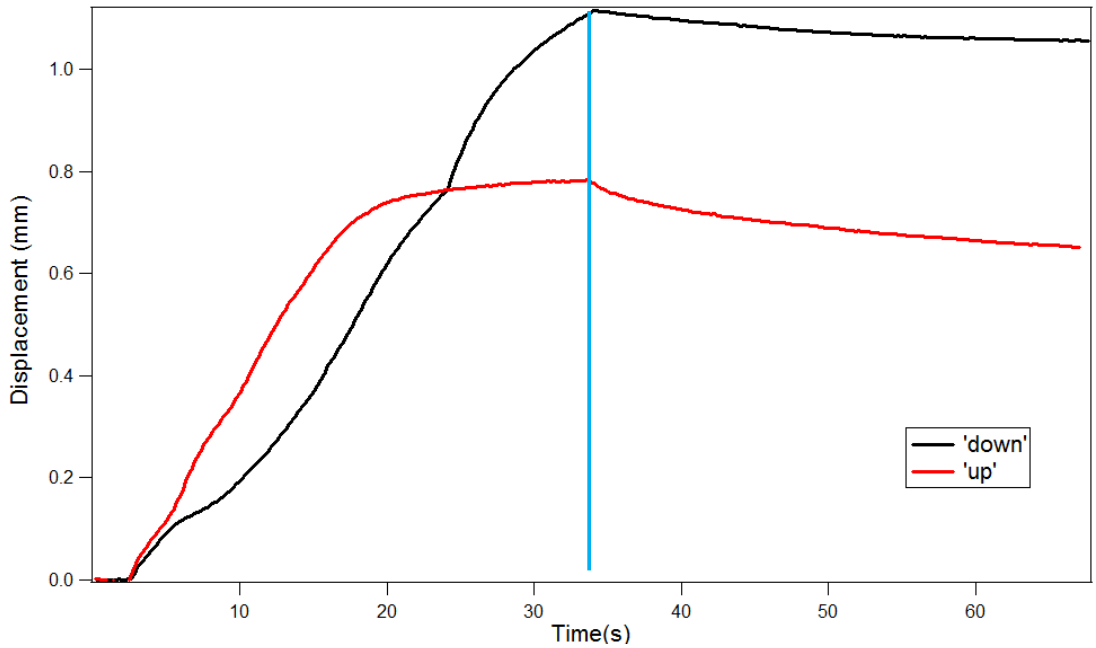


Figure 4.11: Graph of Displacement of The IPMC Micropositioner 2 along Z-axis

4.6 Tilting Movement of IPMC Micropositioner

In Figure 4.12, the IPMC micropositioner tilted the stage in the middle upward with a tilt angle when 2 of the legs (pointed by red arrows) were supplied with 5 V step voltage. The laser spot will be pointed at the position between the 2 legs to detect the maximum displacement. Then the tilt angle can be calculated using trigonometry (shown in Figure 4.13).

Figure 4.12: Tilt Angle Movement of IPMC Micropositioner.

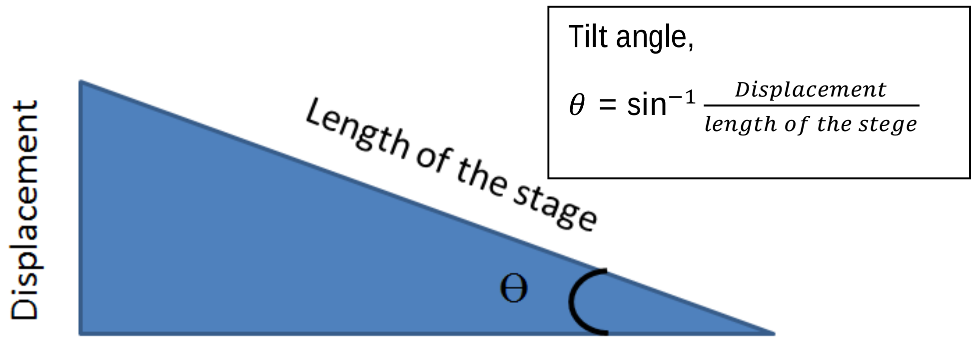


Figure 4.13: Trigonometry used to Calculate Tilt Angle.

The tilt angle calculated from the displacement was shown in the Figure 4.14 and Figure 4.15. Both graph shown exponentially increase in tilt angle when 5 V step voltage is supplied. The power supply was turned off after 14 s for Figure 4.14 and 44.5 s for Figure 4.15. The micropositioner returns to its original position after power supply is turned off.

The micropositioner in Figure 4.14 have maximum tilt angle of 1.51 degree and 0.76 degree for upward and downward tilt angle. The difference between upward and downward tilt angle are large (Percentage Error = $\frac{1.22-0.76}{1.22} \times 100\% =$ ~37.7%). On the other hand, the result shown in Figure 4.15 have same gap between the maximum tilt angle. That micropositioner have maximum tilt angle of 1.345 degree for upward and 1.271 degree for downward tilt angle.

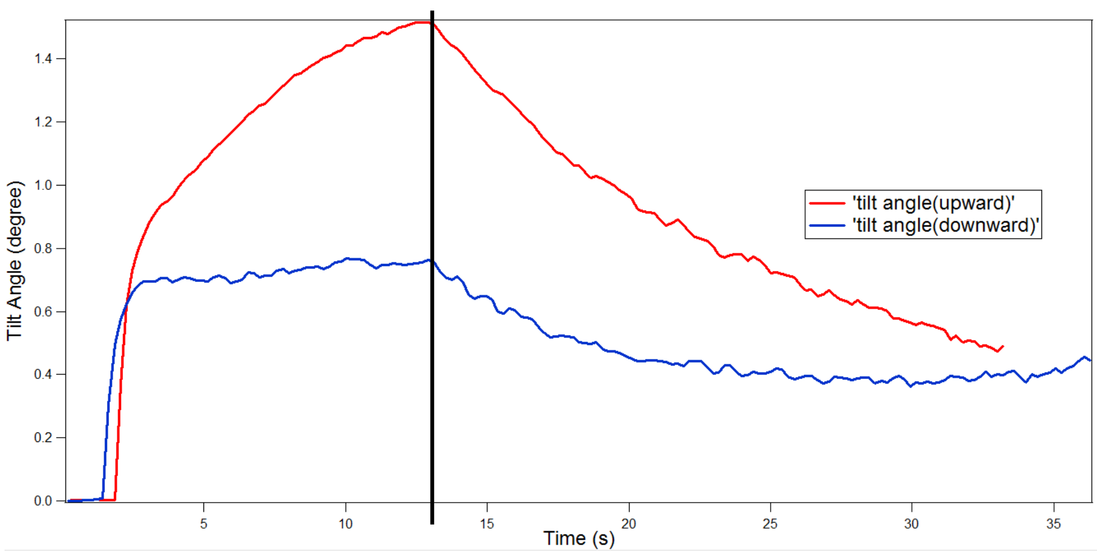


Figure 4.14: Graph of Tilt Angle of IPMC Micropositioner 1 across Time.

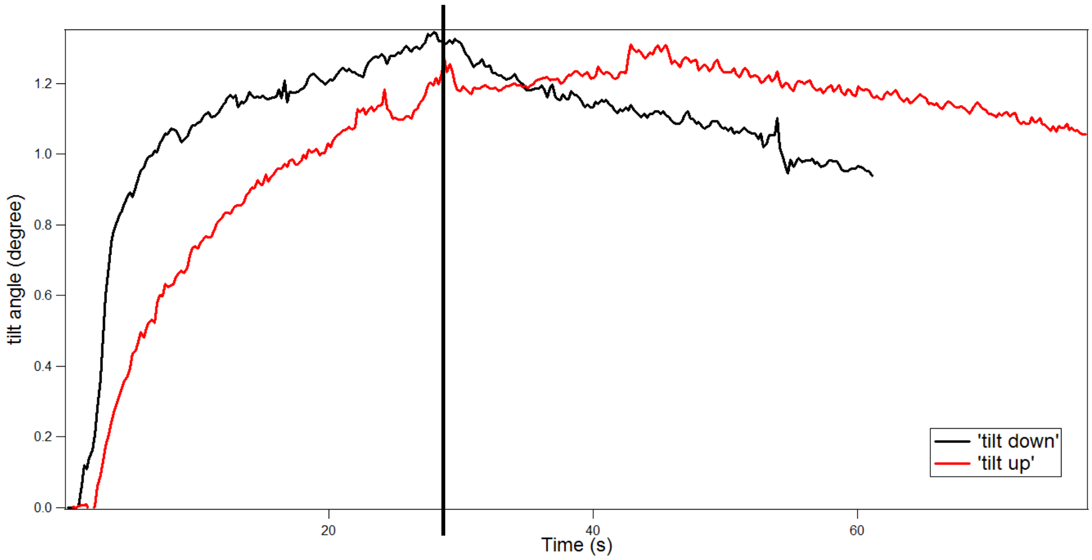


Figure 4.15: Graph of Tilt Angle of IPMC Micropositioner 2 across Time.

In conclusion, the IPMC micropositioner can perform tilting motion with low operating voltage. It successfully achieve ~1.22 degree of tilt angle when supplied with 5 V.

4.7 Summary

IPMC have largest deformation at the area near the point where voltage is supplied and have the largest displacement at the tip of the IPMC strip. So, the clamp design to clamp the IPMC must not block the area with deformation. IPMC shows large potential in application of microactuotor. IPMC can perform different movement by using its bending ability. By integrating IPMC in micropositioner, IPMC can perform z-axis movement and tilting movement.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Monolithic IPMC micropositioner was fabricated using silver mirror method. The fabricated IPMCs were tested under different level of voltage and shows different deflection. According to result, the maximum deflection is shown at the voltage range of 3 V to 4 V. The current response of the IPMC increases when there is change in voltage level.

For the IPMC micropositioner, it successfully perform the desired movement which are the z-axis movement and tilting movement of the stage. It can move the stage up and down by average of 1 mm when 5 V was supplied. It provides a tilting angle for upward and downward tilting by ~1.22 degree when 5 V is supplied.

5.2 Recommendations for future work

IPMC have high potential as actuator. Therefore, study on generation of force is desirable. Relationship of force and voltage can be determined by using load cell or weighing balance as the sensor to detect the force generated. Study also can be conducted for number of load a IPMC actuator can carry for IPMC force analysis.

Other than that, study on response of IPMC when different type of voltage signal is supplied. Voltage signal like AC voltage, pulse width modulated (PWM) DC signal, Square wave AC signal can be input to the IPMC and observe the response of IPMC in term of current, displacement and force. The circuit in Figure 5.1 is the circuit design to produce duty cycle 25%, 50%, 75% and 100% PWM signal of 0 V to 4.6V using PIC 18F. The duty cycle can be changed just by changing the state of the tact switch. This circuit can be used to get the response of IPMC with different duty cycle of PWM signal.

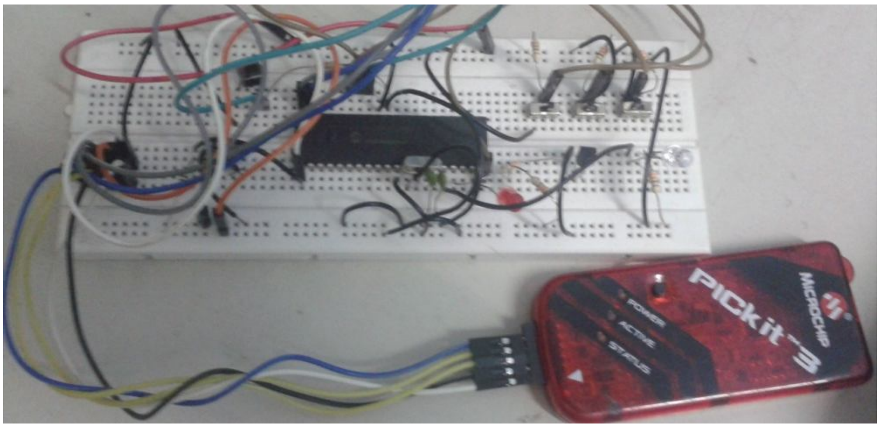


Figure 5.1: Circuit Design to produce PWM Signal using PIC 18F

IPMC not only can be applied to engineering field. It also can be used as a tool in fashion designing. It can be embedded inside cloth, and when voltage is supplied, the design of the cloth can be change in a few seconds.

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