FABRICATION OF IPMC BIOMIMETIC FLAPPING THRUSTER AND ITS SPEED CONTROL BASED ON NAFION MEMBRANE

by

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LIST OF ABBREVIATIONS

BCA	Body/caudal Actuation
DAQ	Data acquisition
DC	Direct coupling
DI	Deionized
EAP	Electroactive polymer
GPS	Global positioning system
IC	Integrated circuit
IMU	Inertial measurement unit
IPMC	Ionic polymer metal composite
JET	Jet propulsion
MPA	Median/paired Actuation
PID	Proportional integral derivative
PVDF	Polyvinylidene difluoride
PWM	Pulse-width modulation
PZT	Plumbum/ lead zirconate titanate
SMA	Shape memory alloy

LIST OF SYMBOLS

Symbol	Description
-SO2F	Sulfonyl fluoride form
–SO3K	Potassium salt form
-SO3Na	Sodium salt form
Ag	Silver
Au	Gold
$e(t)$	Tracking error
$e_{max}(t)$	Maximum tracking error
$e_{rms}(t)$	Root-mean-squared tracking error
F_{max}	Maximum generative force
F_t	Generative force at a certain time
H^+	Hydrogen cation
HCl	Hydrochloric
KOH	Potassium hydroxide
Li^+	Lithium cation
$LiCl_2$	Lithium chloride
M	Molar

$NaBH_4$	Sodium borohydride
NaOH	Sodium hydroxide
NH_2NH_2	Hydrazine
NH_2OH-HCl	Hydroxylamine hydrochloride
NH_4OH	Ammonium hydroxide
Pt	Platinum
$[Pt(NH_3)_4]Cl_2$	Platinum complex
t	Time
Δt	Response time
$\overline{\Delta t}$	Average response time
T_d	Delay time
T_r	Rise time

FABRIKASI PENUJAH MENGIBAS BIOMIMETIK IPMC DAN KAWALAN LAJUNYA BERASASKAN MEMBRAN NAFION

ABSTRAK

Keperluan yang semakin meningkat bagi pengesahan maklumat permulaan yang sebenar dalam ruang kecil untuk mana-mana operasi di bawah air yang melibatkan mencari dan menyelamat, penerokaan arkeologi dan kajian oseanografi telah mendorong pembangunan penujah mengibas biomimetik bawah air yang menggunakan penggerak pintar Komposit Logam Polimer Ionik (IPMC). Walau bagaimanapun, salah satu masalah yang melibatkan penujah seperti ini ialah penjanaan kuasa tujah yang tidak konsisten dan tidak terkawal kerana tiada mekanisma kawalan yang dicadangkan. Oleh itu, objektif utama kajian ini ialah untuk melengkapkan penujah mengibas biomimetik dengan sistem kawalan laju untuk memastikan pergerakan penujah ini akan mengikuti kelajuan yang telah ditetapkan. Pertama, pengesahan pergerakan dan kebolehkawalan penggerak IPMC yang telah difabrikasi dilakukan. Perisian MATLAB/Simulink dan Arduino IDE/PLX-DAQ telah digunakan sebagai konfigurasi kawalan dan perakaman maklumat untuk membangunkan sistem kawalan menggunakan pengawal mikro Arduino. Analisis keputusan tindak balas pemesongan penggerak IPMC yang berdasarkan suap balik pengesan laser membuktikan bahawa penggerak IPMC yang telah difabrikasi berjaya menjejaki isyarat masukan seperti isyarat langkah, gelombang persegi, dan gelombang sinus. Oleh itu, ia mampu menghasilkan pergerakan mengibas yang diperlukan dalam penujah berbentuk ikan. Kemudian penggerak IPMC telah digunakan sebagai sirip belakang penujah untuk menggerakkan badan penujah pada kelajuan tertentu. Satu peranti Unit Pengukuran Inersia (IMU) telah digunakan sebagai pengesan kelajuan dan orientasi dalam eksperimen kawalan gelung terbuka dan gelung tertutup. Keputusan gelung terbuka membuktikan bahawa kelajuan semasa penujah yang dijana bertambah dengan peningkatan amplitud voltan kepada IPMC. Berdasarkan maklumat ini, sistem kawalan gelung tertutup telah dibangunkan, dan prestasinya telah disahkan. Dengan mengawal amplitud voltan, sistem kawalan gelung tertutup berjaya mengawal kelajuan semasa penujah di sekitar sasaran 1.5 cm/s. Kesimpulannya, kelajuan penujah mengibas berasaskan IPMC boleh dikawal secara berkesan dengan menggunakan peranti IMU sebagai maklum balas kelajuan. Pengetahuan penyelidikan ini adalah penting dalam menyediakan satu penyelesaian kepada penyelidik robot biomimetik berasaskan IPMC yang lain untuk mengawal kuasa tujah.

FABRICATION OF IPMC BIOMIMETIC FLAPPING THRUSTER AND ITS SPEED CONTROL BASED ON NAFION MEMBRANE

ABSTRACT

The increasing need for real preliminary information verification in small space for any underwater operations involving search and rescue, archaeological exploration and oceanographic studies had inspired the development of biomimetic underwater flapping thruster using Ionic Polymer Metal Composite (IPMC) smart actuator. However, one of the problems with this kind of thruster is the inconsistent and uncontrollable thrust generation due to no proposed control mechanism. Therefore, the main objective of this research is to equip this biomimetic flapping thruster with speed control system to ensure the motion of this thruster is following the pre-determined speed. Firstly, the fabricated IPMC actuator's actuation and controllability were verified. MATLAB/Simulink and ArduinoIDE/PLX-DAQ interfaces were utilized as control and data logging configurations to develop control system using Arduino micro controller. Results analysis of IPMC actuator deflection response from laser sensor feedback proves that the fabricated IPMC actuator managed to track step, square wave, and sinusoidal wave input signal. Hence, it is capable of producing a flapping actuation that was needed in a fish like thruster. Then the IPMC actuator was utilized as the thruster's caudal fin to move the thruster body at certain speed. An Inertial Measurement Unit (IMU) device was used as the speed and orientation sensor for open loop and closed loop control experiments. Open loop results prove that the generated thruster instantaneous speed increases with the increases of amplitude of voltage to IPMC. Based on this information, a closed loop control system was developed, and its performance was verified. By controlling the voltage amplitude, the closed loop control system managed to control

thruster’s instantaneous speed around the 1.5 cm/s setpoint. In conclusion, the speed of IPMC based flapping thruster can be effectively controlled by using IMU device as a speed feedback. This research knowledge is critical in providing other IPMC based biomimetic robot researcher a solution for controlling the thrust generation.

CHAPTER 1

INTRODUCTION

1.1 Chapter overview

This chapter describes a brief background explanation of the research. It also provides the problem statements, research objectives, scope of studies, and research approaches. The general thesis outline is presented at the end of this chapter.

1.2 Research background

The increasing need for real information verification in a small space especially for any underwater operations involving search and rescue, archaeological exploration and oceanographic studies had inspired the development of biomimetic underwater small robot thruster using smart actuators in recent years (Chu et al., 2012; Roper et al., 2011). This need was strengthen by recent series of high-profile incidents such as Malaysia Airlines Flight MH370 disappearance in Southern Indian Ocean (Wikipedia, 2014b), Indonesia Air Asia Flight QZ8501 crash in Java Sea (Wikipedia, 2014a), and the sinking of MV Sewol ferry in South Korea Sea (Wikipedia, 2014c). During an underwater operation to rescue the victims or to salvage the sunken vehicle body, the rescuer may face difficulties to operate in a tight space inside the sunken vehicle due to limited of surrounding information. Therefore, there is a need for the small underwater robot that can access this tight area. Thus, the development of controllable small underwater robot is being considered in this research.

Fish robots which implemented undulatory and oscillatory actuator movement as propulsion system were introduced (Heo et al., 2007; Low et al., 2006; Chen et al., 2011; Chen et al., 2012; Low, 2007). Moreover, jet propulsion of jellyfish and squid locomotion also were referred in designing underwater robot thruster (Sung-Weon and Il-Kwon, 2009; Yunchun et al., 2007; Alex et al., 2011; Shaari et al., 2013; Joseph et al., 2012). In this kind of biomimetic underwater small robot thrusters or propulsion systems, more compatible smart actuators like ionic polymer metal composite (IPMC), shape memory alloy (SMA) and plumbum/lead zirconate titanate (PZT) were implemented instead of using conventional motor as an actuator. However, this research only focuses on the IPMC actuator; a bending actuator first discovered by Oguro et al. (1993). It is made of ion exchangeable polymer membrane and noble metal electrodes which response to external electric stimulation. The reason for this actuator selection is due to its beneficial properties such as light weight, biocompatibility and its capability to be used directly underwater (Kim et al., 2007b). These properties make IPMC more preferable smart actuator as it can reduce small underwater robot total weight and prevent the usage of costly water proofing accessories. On top of that, IPMC has specific advantages over other smart actuators. IPMC has a superior response over SMA, the important characteristic of excellence actuator. Moreover, IPMC is more suitable for small size robot due to its lower power consumption property compared to PZT (Chu et al., 2012; Bhandari et al., 2012).

However, one of the problems with IPMC actuator based biomimetic underwater small robot flapping thruster is the inconsistent and uncontrollable thrust generation due to no proposed control mechanism (Chen et al., 2012; Sung-Weon and Il-Kwon, 2009; Shaari et al., 2013). Previous researchers proposed direct feedback control using the integrated sensor/actuator scheme that is based on actuator deflection feedback. However, these methods cannot utilize full IPMC actuator potential such as large displacement actuation range (Zheng et al., 2007; Leang et al., 2012; Sisi et al., 2010). Besides, physical bonding between sensor and actuator may interrupt the actuator reaction. There is also a thought of using camera and hydrodynamic knowledge in measuring the system output feedback such as thrust force; similar to experiment done by Sutherland and Madin (2010) which used camera and dye coloring to measure propulsion jet wake of salps organism. But the complicity of measurement and usage of external apparatus restrict the application. Thus, instead of measuring the thrust force directly, speed measurement using Inertial Measurement Unit (IMU) device as a feedback is proposed in this research. Taking inspiration from previously explained underwater robot project, speed control system of IPMC based biomimetic flapping thruster is introduced.

1.3 Problem statements

Three main problems are identified in developing speed control system of IPMC based biomimetic flapping thruster in this research.

(a) Current IPMC actuator cost is very high.

Shipping cost, currency exchange fluctuation, and fabrication costs made imported IPMC actuator price is very high for developing countries researcher. For instance, price for even a small piece of IPMC actuator (5 mm × 30 mm × 0.2 mm) can reach up to USD 200 which is equivalent to MYR 761.80 (exchange rate USD/MYR 3.81) (Environmental Robot Inc., 2015). This high cost restricts any risky testing experiment or development during research work, thus preventing research potential to be achieved. Therefore, for this research usage, fabrication of IPMC actuator is internally conducted to minimize the cost.

(b) Suitable thruster design and fabricated IPMC actuator control configuration are initially undecided.

There are two types of biomimetic thruster designs which are actuated by IPMC actuator: fish robot and jellyfish/squid robot. Which one is the suitable thruster design configuration to this research is initially undecided. Therefore, design feasibility study based on their movement observation inside the aquarium is being conducted to decide the design. After the design is confirmed, it is necessary to decide the IPMC actuator control configuration based on the selected actuation mechanism. Therefore, even though there are many IPMC control related literatures out there (Mallavarapu and Leo, 2001; Richardson et al., 2003; Chen and Tan, 2008; Ahn et al., 2010; Bhat and Kim, 2004), there is still a need to find out and verify whether fabricated IPMC actuator is controllable underwater.

(c) Direct physical integration of feedback sensor with IPMC actuator limits the actuation displacement and generative force.

Chen et al. (2008) stated that the integrated IPMC/PVDF sensory actuator has limitation for IPMC applications where actuator deformation is relatively large. Moreover, sensors physical bonding to the IPMC actuator surface may interrupt the structural and actuation properties of IPMC actuator itself. For example, added sensor stiffness interrupted the generative force versus applied voltage relationship of IPMC as reported by (Nemat-Nasser, 2002). Besides, the electromechanical transduction reaction underneath IPMC actuator like hydrated ion movement and electrolysis may be disturbed by bonded sensor surface (Nemat-Nasser and Li, 2000). Thus, to avoid unnecessary complications, the best way is to avoid any contact between used sensor and IPMC actuator. Unlike conventional and unpractical laser sensor, the compact setup still can be achieved through the use of small IMU device.

1.4 Objectives

The general aim of this thesis is to develop a speed control system of IPMC based biomimetic flapping thruster. For that reason, the following objectives must be achieved.

(a) To fabricate different thicknesses of IPMC actuator using the physical hot pressing method and the chemical electroless plating method.

(b) To configure thruster design and then verify whether fabricated IPMC is controllable based on selected actuation type.

(c) To develop and analyse the performance of a speed control system of IPMC based biomimetic flapping thruster using an IMU device.

1.5 Scope of studies

In this research, IPMC actuator is made of Nafion membrane and Platinum (Pt) electrodes that is fabricated through hot pressing and electroless plating methods. These fabrication methods are chosen because of the reliability and stability that have been reported (Bhandari et al., 2012). Besides, even though there are more advanced materials to produce high-performance IPMC, Nafion membrane and Platinum (Pt) materials are chosen as they are widely used in IPMC research field, hence there are abundant literature reference available (Jo et al., 2013). For IPMC actuator characteristic improvement methods, even though there are many established high impact methods, only repeated reduction and adsorption process, counter ion exchange (Hydrogen cation (H^+) with Lithium cation (Li^+)), preheat