DEVELOPMENT OF ELECTROMYOGRAPHY-CONTROLLED 3D PRINTED ROBOT HAND AND SUPERVISED MACHINE LEARNING FOR SIGNAL CLASSIFICATION

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By

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Chairman : Siti Anom Ahmad, PhD
Faculty : Engineering

Developing a device which resembles the human hand called Anthropomorphic Robotic Hand (ARH) has become a relevant research field due to the needs for the purpose to help the amputees to live their life as normal people. However, the current research state is unsatisfactory, especially in terms of structural design, robot system and the robot control method. In this research, an EMG controlled 3D printed robot hand prototype with improved features and advance hand posture classification method based on EMG signal pattern were proposed. The current state of the robot hand structure development, the structure features do not resemble the human hand functionality with less durability and poor movement capability. In this research, the structural design of the robot hand with five individual actuated fingers and tendon-driven actuator mechanism was designed using the Inventor Professional 2018 software and fabricated it using 3D printing technology. The durability and movement capability of the structure were evaluated through Static analysis (simulation), and validate it through the Load test and Motion capture analysis. As a result, the hand robot structure which made from PLA material can withstand load with 1.5kg while the structure made from ABS material only able to withstand load with 1.4kg in the Static Analysis. After that, the simulation results were validated in the Load Test, and it shows that structure made from PLA material was able to withstand load with 1.7kg while the structure made from ABS material is only able to withstand load with 1.6kg. The result obtained from these experiments shows that the structure made from PLA has better durability than ABS. In another hand, the movement accuracy analysis of the hand robot motion range was performed by comparing the expected motion range and the motion range achieved by 3D printed hand robot. The comparison shows that the similarity percentage achieved is about 72.62% - 98.43%. The accurate motion range and the decent durability were

able to achieve by improving the structural design with the tendon-driven actuator mechanism.

In the system development aspect, the electromyography (EMG) sensors were applied as the main control interface of the system which used to control the hand robot movement transparently to perform the tasks given. The electronic hardware and hand robot structure were integrated to develop an EMG controlled hand robot prototype, and its functionality was tested through three stages: muscular activity detection only, object detection only and the integration of both detection in an algorithm to control the hand robot structure movement to perform opened hand palm and some grasping postures with two trial for each stage. The tasks were performed without any failure and show the developed robot hand is reliable.

Furthermore, the Support vector machine (SVM) and Linear discriminant analysis (LDA) machine learning for the hand posture classification based on the EMG signal pattern were investigated and compared in term of classification performance. The current study of the hand posture classification requires a higher number of EMG sensor used to achieve an accurate classification performance that leads the system to be complicated. In this research, the LDA gives as higher as 85.8% of accuracy with six units of the sensors used compared to SVM which is 85% of accuracy percentage with five units of the sensors used. However, the EMG signal pattern classification was done by SVM has better performance than LDA due to less significant difference in the accuracy percentage, and a fewer number of sensors used by the SVM. The result was achieved with K=15 of fold cross-validation, without PCA and five EMG sensors used that located on the Extensor carpi ulnaris, Extensor digitorum, Extensor carpi radialis, Flexor carpi ulnaris, and Flexor digitorum superficial muscles.

In conclusion, the electromyography controlled hand robot prototype was successfully developed with improved features, optimal structural durability, higher accurate movement capability, reliable system and lower number of sensor used with higher accuracy of the signal pattern classification.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMBANGUNAN ROBOT TANGAN SALINAN 3D KAWALAN ELEKTROMOGRAFI DAN PEMBELAJARAN MESIN BERSELIA UNTUK KLASIFIKASI SIGNAL

Oleh

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Pembinaan tangan robot yang menyerupai tangan manusia sebenar yang dikenali sebagai Anthropomorphic Tangan Robotik menjadi satu kajian yang relevan kerana keperluan untuk membantu orang yang bertangan kudung melakukan aktivity harian mereka seperti manusia yang sempurna. Walau bagaimanapun, terdapat kekangan dalam kajian sedia ada, terutama dalam design struktur, system robot dan kaedah kawan robot yang digunakan. Dalam kajian ini, prototaip robot tangan kawalan penderia Elektromyografi (EMG) dengan ciri-ciri yang telah ditambahbaik dan pengkelasan postur tangan yang maju berdasarkan signal EMG telah dicadangkan.

Dalam struktur tangan robot sedia ada, ciri-ciri struktur masih tidak menyerupai kefungsian tangan manusia yang mempunyai ketahanan dan kemampuan pergerakan yang lemah. Dalam kajian ini, struktur tangan robot ini mempunyai lima jari yang bergerak bebas dan mekanisme penggerak tendon yang didesign menggunakan perisian Inventor Professional 2018 dan dibina menggunakan teknologi cetakan 3D. Ketahanan dan kemampuan pergerakan struktur diuji melalui Analisis Statik (simulasi) dan disahkan melaui Ujian bebanan dan Analisi tangkapan gerakan. Hasil dapatan menunjukkan struktur robot tangan yang diperbuat dari material PLA mampu menahan 1.5kg manakala material ABS pula hanya mampu menahan bebanan sebanyak 1.4kg sahaja melalui Analisis Statik. Selepas itu, keputusan ini disahkan dengan ujian bebanan dan ia menunjukkan bahawa struktur yang diperbuat daripada material PLA mampu mehanan bebanan sebanyak 1.7kg manakala ABS hanya mampu menahan bebanan sebanyak 1.6kg sahaja. Dapatan yang diperoleh dari kedua-dua eksperimen menunjukkan material PLA mempunyai ketahanan yang tinggi berbanding material ABS. Selain itu, analisis ke atas pergerakan bahagian yang bergerak pada robot dijalankan dan juga dibandingkan dengan pergerakan yang sepatutnya dicapai oleh struktur yang telah dicetak 3D. Perbandingan menunjukkan, peratusan persamaan telah mencapai 72.62%-98.43%.

Ketepatan pergerakan dan ketahanan yang cukup memuaskan dapat dicapai dengan menambahbaik design struktur dengan mekanisme pengerak tendon. Di dalam aspek pembangunan sistem pula, penderia elektromyografi digunakan sebagai muka kawalan utama untuk mengawal pergerakan robot dalam melakukan sebarang tugasan. Perkakas elektronik dan struktur tangan robot digabungkan untuk membina prototaip robot tangan kawalan elektromyografi and kefungsiannya diuji melalui tiga tahap: pengesan aktiviti otot, pengesan objek sahaja dan penggambugan kedua-dua pengesanan dalam satu algorithma untuk mengawal tangan robot dalam melakukan postur struktur seperti tangan terbuka dan menggenggam untuk dua percubaan bagi setiap tahap. Prototaip ini mampu melakukan tugasan yang telah diberikan tanpa mengalami sebarang kegagalan.

Selain itu, Mesin Vektor Sokongan dan Analisis Diskriminasi Lurus untuk pengkelasan postur tangan menggunakan signal EMG dikaji dan dibandingkan dalam persembahan pengkelasan. Kajian sediaada mengenai pengkelasan postur tangan memerlukan penderiaan EMG yang banyak untuk mencapai ketepatan yang tinggi yang merumitkan lagi system yang dibina. Dalam kajian ini, LDA menghasilkan peratusan yang tinggi iaitu 85.8% dengan enam unit penderia berbanding SVM hanya 85% ketepatan dengan lima unit penderia. Namun begitu, pengkelasan paten isyarat EMG yang dihasilkan oleh SVM memberi persembahan yang terbaik berbanding LDA. Hal ini kerana peratusan yang dihasilkan tidak menunjukkan perbezaan yang ketara Antara kedua-dua jenis mesin pembelajaran dan SVM menggunakan sedikit bilangan penderia. Tambahan pula, SVM menggunakan K=15 Lipatan Pengesahan Silang, tanpa PCA dan lima unit penderia yang ditampalkan ke otot Extensor Carpi Ulnaris, Extensor Digitorum, Extensor Carpi Radialis, Flexor Carpi Ulnaris, dan Flexor Digitorum Superficial.

Konklusinya, prototaip robot tangan kawalan EMG telah berjaya dicipta dengan struktur yang mempunyai ciri-ciri yang ditambahbaik, berketahanan optimal, kemampuan ketepatan dalam pergerakan yang tinggi, system yang boleh dipercayai dan kurang penggunaan penderia serta mampu mencapai peratusan yang tinggi dalam pengkelasan paten isyarat EMG.

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"MAY ALLAH, THE ALMIGHTY BLESS ALL THE PERSONALITIES WHO HAD DIRECTLY OR INDIRECTLY HELPED ME TO ACHIEVE MY GOALS "

I certify that a Thesis Examination Committee has met on 21 November 2019 to conduct the final examination of Mohamad Aizat bin Abdul Wahit on his thesis entitled "Development of Electromyography-Controlled 3D Printed Robot Hand and Supervised Machine Learning for Signal Classification" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This is to confirm that:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	Three Dimension
ABS	Acrylonitrile Butadiene Styrene
AM	Addictive Manufacturing
APH	Anthropomorphic Prosthetic Hand
BR	Brachioradialis
CAD	Computer-Aided Design
DIP	Distal Interphalangeal
DP	Distal Phalanx
DRH	Dexterous Robotic Hand
ECRL	Extensor Carpi Radialis Longus
ECU	Extensor Carpi Ulnaris
EDG	Extensor Digitorum
EM	End muscle
EMG	Electromyography
FCRL	Flexor Carpi Radialis Longus
FCU	Flexor Carpi Ulnaris
FDM	Fused Deposition Modelling
FDS	Flexor Digitorum Superficialis
GND	Ground
IEMG	Intramuscular Electromyography
IP	Intermediate Phalanx
IR	Infra-red
JCC	Joint Coupling Connector
LDA	Linear Discriminant Analysis
MCP	Metacarpophalangeal
MM	Mid muscle
MU	Motor Unit
PC	Personal Computer
PCA	Principal Component Analysis
PIP	Proximal Interphalangeal
PL	Palmaris Longus
PLA	Polylactic Acid
PP	Proximal Phalanx
SEMG	Surface Electromyography
SIG	Signal
SM	Subtractive Manufacturing
SVM	Support Vector Machine
VCC	Voltage Common Collector

CHAPTER 1

INTRODUCTION

As reported in the year 2012 of Statistical Bulletin by the Social Welfare Department of Malaysia, there are 350,000 people out of the Malaysian population registered themselves as a disabled person, and 34% of this number is categorised as upper limb amputees and paralysed physical disabilities class [1]. By observing the Malaysian population over the year from 2009 until 2019, the population number became significantly grows, as well as the percentage probability of the disabled person in those years. This fact shows the importance of research in the development of robotic hand field as an effort to help these people live their daily life as normal people.

In the development of the robot hand device, there are two different paths called the Dexterous Robotic Hand (DRH) and the Anthropomorphic Prosthetic Hand (APH). The differences between these two routes can be differentiated based on the focus of the robot application and its function [2]. For example, the development of DRH is to emphasise the efficiency and speed response to do a complicated task. However, this may cause the system looks bulky. Meanwhile, the development of APH is to emphasise the reliability and the aesthetic value of the robot that resembles the human hand looks which may help the disabled to perform their daily tasks in a way that more natural. This system usually can perform simple tasks such as opened hand palm and basic grasping posture.

Over the past few decades, this research had experienced the evolution of the robot control method, which involves the exchange of robot controlled by the Electromyography (EMG) sensor from the use of conventional joystick controller. The EMG signal is the signal collected from the human body by using EMG sensor do not resemble which provides a neuromuscular activity that suitable to be used as a signal interface for robot control [3]. This control interface is a transparent controller that allows the user to control the robot as their body part and becomes the most control interface used among the researchers to control the prosthesis [4]. The way to increase the number of hand posture variation, it requires artificial intelligence support as machine learning to recognise and classify the EMG signal pattern into several classes of hand postures. Recently, lot of researchers used different pattern recognition techniques to achieve the accuracy in hand posture classification that include the uses of pre-processing techniques, data mining techniques and machine learning technique (i.e. artificial neural networks, genetic algorithms, fuzzy logic, self-organizing neural network and support vector machine) [5, 6, 7, 8, 9].

In the conjunction of Industrial Revolution 4.0, the growing of the prosthetic hand research field has been fully supported, and it triggers onto a bigger revolution in term of design and fabrication of the product with the development of 3D printing technology. This technology encouraged the researcher to produce the printable prosthetic hand design. Besides, it makes the robot designed on fully customisable to the wearer. So, the wearer feels comfortable while wearing the device. The prosthetic hand now becomes the do-it-yourself device as it can be printed easily by anyone and anywhere virtually.

1.1 Problem Statement and the Importance of Research

The robot hand is a device that resembles human hand functionality that been used to replace the missing anatomical segments from the elbow to the hand or known as the below-elbow amputees. However, there are some shortcomings discovered in the current study regarding the structural design of the robot hand itself. Most researchers came out with incomplete fingers and joints robot hands which do not resemble the actual human hand [10]. Also, the cable-driven actuator mechanism is widely used by researchers to move the robot hand joints [11, 12, 13, 14, 15, 16]. However, there are some drawbacks of using the mechanism such as inaccurate motion range and poor structure durability. This is because of the mechanical properties of the cable that is easily changing and its length that often extends over the time [17, 18]. Furthermore, each of the fingers has not unindividual actuated fingers and the existing robot hand structure is bulky in size compared to the average size of the human hand [19, 20]. The metal that often been used as a material for the robot hand structures makes the robot hand structure does not suitable for prosthetics use as it is weighty compared to the structure made of plastics [21]. The evolution of the robot control method happens, the electromyography (EMG) sensor widely used for this application instead of using the conventional joystick controller. The muscular activity information is measured and used as the input interface to the system which allows the user to control the robot as like their body part. In an effort to improve robot control capabilities it requires the machine learning to classify acquired signal patterns. Currently, the Support Vector Machine (SVM) and Linear Discriminant Analysis (LDA) machine learning are widely used for robot hand controls. However, it requires a large number of sensors to obtained high accuracy in signal classification which negatively affects the complexity of the robot hand system [9, 22, 23].

1.2 Aim and Research Objectives

The project aims to develop an EMG controlled 3D printed robot hand prototype based on the supervised machine learning to classify the hand postures.

The objectives are:

- To design the robot hand structure and fabricate it by using the 3D printing technology and validate the structure durability and movement capability;
- To develop the EMG controlled 3D printed robot hand prototype and test its functionality.
- To develop the EMG controller of the robot hand system for the hand posture classification by using a supervised machine learning method.

1.3 Hypothesis

Supervised machine learning of EMG signal classification to achieve human hand posture capability.

1.4 Significance of the Study

In this research, a real-time EMG controlled robot hand prototype with five independent actuated fingers, including the thumb, was developed. Moreover, the five fingers robot hand structure with optimal durability and movement capability was developed. Other than that, the signal processing analysis of the EMG signal pattern was done. Besides, the efficient controller for EMG signal classification for eight types of hand postures was proposed.

1.5 Research Scope

The scope of this research includes the following:

- The research is divided into two main part, the Part I is about the development of electromyography controlled 3D printed robot hand prototype using the threshold voltage comparison method and the Part II is about the classification of the EMG signal pattern which is performed in post-processing. The combination of these two parts for the future works.
- The planar rigid body motion for the structural design is limited on the sagittal plane only.
- The finger structure of the robot for the index, middle, ring and baby finger is assumed a similar size.
- The robot finger movement excludes the non-linearities condition.
- The number of hand postures used for classification is only eight postures, and the wrist movement is excluded from the hand postures.
- The hand postures are focusing on the movement of the five fingers of the right hand.

1.6 Thesis Outline

This thesis is divided into five chapters.

Chapter 2 is a literature review regarding the current robot hand device and the 3D printed robot hand structure which are available in the market nowadays. There is also the description of the EMG sensor and human muscular system that also includes, the reviews about the structure durability validation techniques, the explanation of EMG signal processing analysis techniques such pre-processing, feature extraction, classifier, data reduction and cross-validation techniques.

In Chapter 3, you can find the explanations of the structure of the methodology in comprehensive steps and procedures that includes the architecture for the structure and system development of the EMG controlled robot hand in details and the procedures of the EMG signal samples preparation techniques. There are also explanations of the analysis techniques on the EMG signal pattern classification for both SVM and LDA. Furthermore, the training and testing techniques also described in this chapter.

In Chapter 4, the 3D printed robot hand structure designed is fabricated, and its durability and movement capability are evaluated. The pre-processing of the EMG signal analysis also performed, and the system functionality is validated by performing the basic task using a basic controller. In this chapter also, the EMG signal classification of the system was upgraded to perform the complex task by using the artificial intelligent machine learning such as SVM and LDA to classify the EMG signal pattern.

Last but not least, Chapter 5 consists of summarized outcomes, the contribution of the study and emphasised on the recommendation to improve future innovation.

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