UNIVERSITI PUTRA MALAYSIA

REAL TIME SELF-CALIBRATION ALGORITHM OF PRESSURE SENSOR FOR ROBOTIC HAND GLOVE SYSTEM

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By

AHMED M. M. ALMASSRI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

January 2019

DEDICATION

This thesis is wholeheartedly dedicated to:

My praiseworthy parents (**MOHAMMED BADEI & ROWAIDA**),

My most beloved wife **ASMAA,**

My first beautiful daughter **GHAZL,**

My brothers and sister

And lastly, we dedicated this work to the **Almighty GOD**, thank you for the guidance, strength, power of mind, protection and skills and for giving us a healthy life. All of these, we offer to you.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

REAL TIME SELF-CALIBRATION ALGORITHM OF PRESSURE SENSOR FOR ROBOTIC HAND GLOVE SYSTEM

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January 2019

Chairman: Prof. Wan Zuha Wan Hasan, PhD
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This study investigates the use of a novel Proposed Self-Calibration Algorithm (PSCA) of multi pressure sensors in real time on robotic hand glove system. The PSCA should be able to fix major problems in the pressure sensor including hysteresis, variation in gain and lack of linearity with high accuracy. The traditional calibration process for FlexiForce sensor used is a time-consuming task because it is usually done through manual and repetitive identification [1, 2]. Furthermore, a traditional computational method is inadequate for solving the problem since it is extremely difficult to resolve the mathematical formula among multiple confounding pressure variables [1, 3, 4]. In traditional calibration method of FlexiForce sensor, the maximum calibration time is 20 min and the signal decrease is equal to 83% for sinusoidal excitations of frequency, amplitude, and mean value as reported in [5]. Accordingly, this study proposed a new method to predicting self-calibration in a pressure sensor using Levenberg Marquardt Back Propagation Artificial Neural Network (LMBP-ANN) model.

The proposed method was achieved using one-hour calibration data set of pressure sensor in real time. The collected measurements were shown to lead to lack of linearity and fluctuation in output pressure sensor over time which should be compensated. The proposed method was validated by comparing the output force of PSCA with the experimental target force from load cell (reference). This work shows that the Proposed model exhibited a remarkable performance than traditional methods with a max MSE of 0.17325 and R value over 0.99 for the total response of training, testing and validation. The model was tested using an untrained input data set in order to verify the Proposed model's capability for implementing a self-calibration algorithm. We find that, the Proposed LMBP-ANN model for self-calibration purposes is able to successfully predict the desired pressure over time, even the uncertain behaviour of the pressure sensors due to its material creep.

Developing an intelligent wearable robotic hand glove system based on PSCA with self-calibration feature of grasping mechanism is implemented. Then grasping sampled objects (plastic bottle and sponge ball) with different weights based on the developed robotic hand glove system were successfully performed. The results proved that the PSCA has the ability to successfully and accurately estimate the desired grasping forces in real time even the decrease and fluctuation of the forces pattern in sensor response. Afterwards, the PSCA was implemented and tested in real time based on MCU and software (MATLAB). For validity and performance purpose of PSCA, the MSE and MAPE are calculated of 0.30 and 1.21% base on MCU and 0.08 and 0.6 base on MATLAB respectively.

Overall, the PSCA presented here ensure that the problems of hysteresis, variation in gain and lack of linearity over time have overcome. Furthermore, we have obtained accurate measurements of grasping mechanism. This provides a useful methodology for the user to evaluate the performance of any measurement system in a real-time environment.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

MASA NYATA ALOGRITMA KALIBRASI KENDIRI BAGI PENGESAN TEKANAN UNTUK SISTEM SARUNG TANGAN ROBOTIK

Oleh

AHMED M. M. ALMASSRI

Januari 2019

Pengerusi: Madya Wan Zuha Wan Hasan, PhD
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Kajian ini menyiasat penggunaan Algoritma Diri Penentukuran Diri (PSCA) yang baru dari sensor pelbagai tekanan dalam masa nyata pada sistem sarung tangan tangan robot. PSCA harus dapat menyelesaikan masalah utama dalam sensor tekanan seperti histeresis, variasi keuntungan dan kekurangan linearity dengan ketepatan yang tinggi. Proses penentukuran tradisional untuk jenis sensor ini adalah tugas yang memakan waktu kerana biasanya dilakukan melalui pengenalan manual dan berulang [1, 2]. Selain itu, kaedah pengiraan tradisional tidak mencukupi untuk menyelesaikan masalah kerana amat sukar untuk menyelesaikan formula matematik di antara pemboleh ubah tekanan yang berbeza-beza [1, 3, 4]. Oleh itu, kajian ini mencadangkan kaedah baru untuk meramalkan penentukuran diri dalam sensor tekanan menggunakan model Lederberg Marquardt Back Propagation Network Neural Buffer (LMBP-ANN).

Kaedah yang dicadangkan dicapai menggunakan set data yang dikumpulkan oleh sensor tekanan dalam masa nyata. Pengukuran yang terkumpul ditunjukkan untuk menyebabkan kekurangan linearity dan turun naik dalam sensor tekanan output dari masa ke masa yang harus dikompensasi. Kaedah yang dicadangkan telah disahkan dengan membandingkan kekuatan output rangkaian terlatih dengan daya sasaran eksperimen (rujukan). Kerja-kerja ini menunjukkan bahawa Model yang dicadangkan menunjukkan prestasi yang luar biasa daripada kaedah tradisional dengan nilai MSE maksimum 0.17325 dan nilai R melebihi 0.99 untuk jumlah tindak balas latihan, ujian dan pengesahan. Model ini diuji menggunakan set data input yang tidak terlatih untuk mengesahkan keupayaan model Cadangan untuk melaksanakan algoritma penentukuran diri. Kami mendapati bahawa, model LMBP-ANN yang dicadangkan untuk tujuan penentukuran sendiri dapat berjaya meramalkan tekanan yang diinginkan dari masa ke masa, walaupun perilaku tekanan tekanan yang tidak menentu disebabkan oleh rayapan materialnya.

Membangunkan sistem sarung tangan robotik yang berpakaian pintar berdasarkan PSCA dengan ciri penentukuran diri mekanisme menggenggam dilaksanakan. Kemudian memegang objek sampel (botol plastik dan bola span) dengan berat yang berlainan berdasarkan sistem sarung tangan robotik yang telah berjaya dilaksanakan. Hasilnya membuktikan bahawa PSCA mempunyai keupayaan untuk secara tepat dan tepat menganggarkan daya tarikan yang dikehendaki dalam masa nyata walaupun penurunan dan turun naik pola daya dalam tindak balas sensor. Selepas itu, PSCA dilaksanakan dan diuji dalam masa nyata berdasarkan MCU dan perisian (MATLAB). Bagi tujuan sah dan prestasi PSCA, MSE dan MAPE dikira berdasarkan 0.30 dan 1.21% berdasarkan MCU dan 0.08 dan 0.6 berdasarkan MATLAB masing-masing.

Secara keseluruhannya, PSCA yang dibentangkan di sini memastikan bahawa masalah histeresis, variasi keuntungan dan kekurangan linearity dari masa ke masa telah diatasi. Selain itu, kami telah memperolehi ukuran yang tepat untuk merakam mekanisme. Ini menyediakan metodologi berguna untuk pengguna untuk menilai prestasi sebarang sistem pengukuran dalam persekitaran masa nyata.

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I certify that a Thesis Examination Committee has met on 17 January 2019 to conduct the final examination of Ahmed M. M. Almassri on his thesis entitled "Real Time Self-Calibration Algorithm of Pressure Sensor for Robotic Hand Glove System" 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 Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

PSCA	Proposed Self-Calibration Algorithm
DAQ	Data Acquisition
LMBP-ANN	Levenberg Marquardt Back Propagation Artificial Neural Network
ANN	Artificial Neural Network
ANNs	Artificial Neural Networks
BP	Back-Propagation
CVA	Cerebral Vascular Accident
RT	Real Time
QOL	Quality Of Life
VR	Virtual Reality
NMES	Neuromuscular Electrical Stimulation
MEMS	Microelectromechanical Systems
DOF	Degree Of Freedom
ROM	Range Of Motion
PPS	Pressure Profile Systems
MOS	Metal Oxide Semiconductor
MSE	Mean Square Error
LMBP	Levenberg Marquardt Backpropagation
PPA	Progressive Polynomial Algorithm
PVA	Permutation Vector Analysis
MCU	Microcontroller
PIC	Programmable Interface Controller

MLP	Multiplayer Perceptron
RBF	Radial Basis Function
PWM	Pulse Width Modulation
IP	Interphalangeal Joint
avg	Average
sum	Summation
Max	Maximum
min	Minutes

CHAPTER 1

INTRODUCTION

1.1 Overview

Pressure sensors are essential elements in various modern robotic applications, especially robotic hand, due to their ability to facilitate data acquisition (DAQ) and to develop an actual measurement system. Day by day, the applications of robotic hand become more important in our daily life, as it involves the environment, grasping objects, performing tasks or even emulating the human hand. Some types of robotic hands have been implemented for various purposes such as dexterous manipulation [6, 7], artificial limbs [8], grasping objects [9, 10], rehabilitation applications [11-13] and pick and place applications [14]. However, in rehabilitation applications, especially for hand paralysis, the development of wearable robotic hand glove based on multi pressure sensors is crucial towards successful rehabilitation. The development of measurement system to generate a secure grasping robotic hand glove involves the design of an adequate model with the least possible calibration time and highly accurate measurement data. Furthermore, it should be able to address different input sensors [2, 15] and at the same time be able to overcome the nonlinearity output signal issue.

Generally, in the field of medical robotic applications for rehabilitation purposes, several effective techniques are introduced to improve the grasping mechanism of paralysed hand. For instance, SaeboGlove commercial one is used as premier functional solution for impaired hand function [16]. Although the SaeboGlove had used in the normal grasping mechanism, there is no robotic hand glove yet applying a sensing mechanism for secure grasping based on SaeboGlove design.

However, as time elapses during manipulation and grasping in real time (RT), some pressure sensors parameters are changed due to hysteresis, variation in gain and lack of linearity [2, 17]. These negatively affect the calibrated output data. Thereby, inaccurate pressure measurements appear. This implies that the sensors should be compensated in order to eliminate the systematic errors and to ease the calibration too. In fact, the calibration time and accurate performance of a pressure sensor are the most features to be processed in order to effectively linearize the output signal sensors.

Previous traditional methods to analyse and model output signal sensors have been introduced [18-23]. These methods are a time-consuming task because calibration is usually done by manual and repetitive identification [24]. In addition, former calibration algorithms for intelligent sensors such as pressure sensor have been implemented [15, 25-29]. Nevertheless, these algorithms can be applied specifically for a particular sensor but are not appropriate to be used in a general measurement system and the calibration cost is still high. On the other hand, one study investigated the same proposed pressure sensor that was tested herein [5]. A nonlinear model based on traditional computational methods was proposed. Unfortunately, this model couldn't be applied in a real time when a high measurement accuracy for multiple sensors is needed. The mathematical relationship, through data interpolation using a traditional computational method, was inadequate for solving the problem. Accordingly, in this case, a self-calibration algorithm based on an artificial neural networks (ANNs) is recommended to overcome the aforementioned issues.

Currently, ANNs have used for linearization in which the transfer function response curve of the sensor can be identified and the amplifiers linearized [30, 31]. ANNs are advantageous because feedforward networks are universal approximators capable of learning continuous functions with any desired degree of accuracy [32]. In most cases, ANN model has trained using the back-propagation (BP) algorithm [1]. ANNs offer a reliable tool that can model and predict complex problems [3]. It has the ability to capture complex interactions between different variables with a high self-learning capability.

Therefore, based on the aforementioned advantages of ANN, this study Proposed Self-Calibration Algorithm (PSCA) based on the Levenberg Marquardt Back Propagation Artificial Neural Network (LMBP-ANN) model. Our approach provides a self-calibration method to multi pressure sensors based on wearable robotic hand glove. After that a secure grasping robotic hand glove through sensing method as well as self-calibration features of grasping mechanism have been achieved.

1.2 Problem Statement

The number of world's patients with a disability in a part of the body as a result of a cerebral vascular accident (CVA) or stroke is increasing concurrently with the aging of the world population [33]. In fact, some of disabled people suffer from impaired hand while others have paralysis due to stroke and spinal cord injury [34]. Accordingly, the rehabilitation of paralysed hand can be achieved by wearable robotic hand glove that able to enhance the grasping mechanism and improve the hand movement.

However, in the normal grasping mechanism using the SaeboGlove, there is no robotic hand glove yet applying a sensing mechanism for secure grasping based on SaeboGlove design. In addition, despite superior mechanical properties of SaeboGlove, it has not been used yet in designing multi pressure sensors with features of sensing mechanism. Herein, identifying the features of sensing mechanism becomes a significant research area [35].

In fact, as time elapses during grasping and manipulation in real time (RT) using robotic hand glove, some pressure sensors parameters are changed due to hysteresis, variation in gain and lack of linearity [2, 17]. These negatively affect the calibrated output data. Thereby, inaccurate pressure measurements appear. This implies that these sensors should be compensated in order to eliminate the systematic errors and to ease the calibration too. Accordingly, a real time self-calibration algorithm of pressure sensor is proposed to overcome the aforementioned issues. Indeed, without applying PSCA on the robotic hand glove system, the features of the measurement system and the sensing mechanism can’t correctly identify. Leading to inaccurate pressure measurement and increasing the maintenance costs of measurement system [2].

Several traditional procedures and methods have performed to efficiently analyze the algorithm of measurement systems in RT [27]. The traditional calibration process for pressure sensor is a time-consuming task because it is usually done through manual and repetitive identification [1, 2]. Furthermore, a traditional computational methods are inadequate for solving the problem due to high difficulty to resolve the mathematical formula among multiple confounding pressure variables [1, 3]. Due to that the artificial neural networks technique is recommended to implement the real time self-calibration algorithm of pressure sensor in real time.

ANNs offer a reliable tool that can model and predict complex problems [3]. It has the ability to capture complex interactions between different variables with a high self-learning capability. Thereby, based on the aforementioned advantages of ANN, this study presents a novel multi pressure sensor self-calibration estimation method in real time based on the Levenberg Marquardt Back Propagation Artificial Neural Network (LMBP-ANN) model.

Applying the PSCA using LMBP-ANN model based on a wearable developed robotic hand glove especially, for grasping application, promise to increase patient's hand strength and enhance the grasping mechanism. In addition, the Proposed system is capable of providing a secure grasping robotic hand glove through sensing method. In return, this can be used to enhance the durability of grasping mechanism, leading to a more robust and secure grasp.

1.3 Research Objectives

The aim of this research is to improve and enhance the capability of grasping mechanism as well as create a secure grasping robotic hand glove. To conduct this we aim to apply the pressure sensing system on robotic hand glove based on self-calibration algorithm. The main objectives of this research are:

i. To design and apply a real time self-calibration algorithm using artificial neural network based on uncalibrated pressure sensor.

ii. To enhance the capability of grasping mechanism and enhance the secure grasping robotic hand glove through sensing method based on the Proposed algorithm.

iii. To develop an intelligent wearable robotic hand glove system with self-calibration feature of grasping mechanism.

1.4 Research Scope

This research focuses on the development of wearable robotic hand glove system for grasping mechanism and rehabilitation purpose. The artificial neural network technique is used to implement a real time self-calibration algorithm of uncalibrated pressure sensor. However, the SaeboGlove commercial one is used as the platform for the Proposed system and it is developed to generate a secure grasping robotic hand glove. The lightweight, low-profile functional design is just one of the many innovative features that are offered with the SaeboGlove. Furthermore, full joint finger motion possible to maximize functional performance, silicone covered finger tips to improve traction during grasping, non-slip liner to minimize migration. In addition, the used glove includes Lycra material for expandability and palm exposed to increase breathability and ease of donning.

On the other hand, the SaeboGlove has not provided yet with sensing mechanism enhances the capability of grasping mechanism. Thus, installation and applying multi pressure sensors on the fingers of SaeboGlove are important towards enhancing of sensing mechanism. The type of selected sensor is a piezoresistive FlexiForce sensor that has three ranges of force. According to the proposed design, the selected force is 0-25 lbs (110N) that is suitable with the required maximum force. Since in recent experiments, it has been found that the typical maximum finger force produced by humans is no higher than 30 N [36]. The sensing area of 0.375" in diameter (9.53 mm) and 0.008" in thickness (0.208 mm). The operating temperature is -9°C to 60°C.

Basically, in this study, real time calibration of pressure sensors is desired so that the implementation is done in a dynamic environment. Accordingly, the dynamic loading on the sensing area of FlexiForce sensor was applied using the CT3 Texture Analyser machine. The CT3 Texture Analyser with the standard cylinder probe made from plastic clear acrylic of 52.4 mm in diameter, 21 g and 35 mm long was used to apply a force on the sensing area of the pressure sensor. The diameter of the probe (52.4 mm) is larger than the sensing area of the sensor (9.53 mm) and the diameter of puck (8.75 mm) in order to imitate the real-world desired application and increase the performance output results. The proposed test speed of the machine probe is 0.1 mm/s, which takes into consideration the sensor’s thickness (0.208 mm). The maximum load to apply on the pressure sensor was selected to an upper value of 45N which is compatible with the typical maximum finger force produced by humans (30N).

Generally, rehabilitation of the upper limbs is crucial for paralysed patients; one hour of repetitive exercise every session is desired to recover the hand function, which is executed within three stages with 20 min for every stage. Accordingly, three experiments with different conditions were performed to cover the entirety of the rehabilitation period as well as to generalise the Proposed algorithm. This method ensures to achieve a remarkable performance and high accuracy in the calibrations results.

1.5 Research Contribution

This research aims to develop a real time self-calibration algorithm for a pressure sensor to enhance the capability of grasping mechanism and create a secure grasping robotic hand glove. The developed algorithm has implemented based on Proposed Levenberg Marquardt Back Propagation Artificial Neural Network (LMBP-ANN) model.

In addition, this research contributes to the medical sector by developing a robotic hand glove system with high features of sensing mechanism. The PSCA promotes the sensing mechanism by fixing major problems in a pressure sensor include hysteresis, variation in gain and lack of linearity with high accuracy. Which in return, can be used to enhance the durability of the grasping mechanism, leading to a more robust and secure grasping robotic hand glove.

The Proposed LMBP-ANN model is able to successfully predict the desired pressure forces over time, even the uncertain behaviour of pressure sensors due to its material creep. Furthermore, the exposed analysis approach in this research can be a useful methodology for the user to evaluate the performance of any measurement system in a real-time environment.

Other contributions of this research are: the developed robotic hand glove is wearable and lightweight and can provide help in rehabilitation exercises with self-calibration feature of grasping mechanism. This allows patients to return home and perform everyday activities without needed to visit hospital in every rehabilitation session.

1.6 Thesis Layout

This thesis carries out the modelling of a pressure sensor prediction using the self-calibration algorithm based on neural network technique. Also, the linearization of the pressure sensor is carried out using the Proposed LMBP-ANN model. This thesis is organized into seven chapters. Chapter 1 introduces a general overview to the subject and the problem statement. This initiates the research to overcome the current problem. After that, the chapter explicitly explained the objectives to be met as outcome as well as the research scope to be carried out for this research. Eventually, the layout and summary of this thesis are also presented as the last two sections of this chapter.

Chapter 2 presents the literature review related to the research topic. First section outlines the pressure sensor and its application. The rehabilitation system of upper limb and the grasping capability are discussed in the next section. After that this chapter provides the process steps used to develop the robotic hand glove system as well as the implementation of the Proposed algorithm are also introduced. Finally, the basics of neural network, the training methods and the applications used are presented. Subsequently developing self-calibration algorithm is the last section discussed in details.

Chapter 3 illustrates the applied methodology carried out to achieve the objectives and discusses the steps that are taken to apply a real time self-calibration algorithm of uncalibrated pressure sensor based on the ANN. The development of robotic hand glove system based on Proposed algorithm is also discussed. At the end, the experimental setup of Proposed system is prepared.

Consequently, Chapter 4 presents the results with discussions for the Proposed method of stage 1. The results analysis of pressure sensors used based on pressure measurement system are demonstrated. Then the data collection and analysis are presented.

Chapter 5 presents the results of the proposed method of stage 2. The training and evaluation of the PSCA based on LMBB-ANN model are presented. The performance and regression between input and target are also investigated. Finally, testing and evaluation of the PSCA with untrained data set are implemented.

Next, Chapter 6 shows the results of the proposed method of stage 3. The developing of robotic hand glove system based on PSCA is presented. Real time grasping sampled object with different weights based on the developed robotic glove system is investigated. The performance, accuracy and validity of the PSCA are tested with real time input data using MCU and MATLAB.

Finally, Chapter 7 concludes this study with detailed discussions and recommendations for future research.

1.7 Summary

A comprehensive introduction to develop an intelligent wearable robotic hand glove system for self-calibration feature of grasping mechanism is outlined in this chapter. In addition, the problem in confounding pressure variables due to hysteresis, variation in gain and lack of linearity is also investigated. The previous works have faced with some difficulties in this field, which led this study to propose a new approach that can be implemented to overcome the current weakness. This study presents a novel approach to predicting the self-calibration of a pressure sensor in real time based on LMBP-ANN model. To complete the proposed method, a large number of investigations with lots of analysis are implemented so that the outcome of this research can overcome the obstacles.

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LIST OF PUBLICATIONS

Journal Articles

A. M. ALmassri, C. Wada, W. W. Hasan, and S. Ahmad, "Auto-Grasping Algorithm of Robot Gripper Based on Pressure Sensor Measurement," PERTANIKA JOURNAL OF SCIENCE AND TECHNOLOGY, vol. 25, pp. 113-121, 2017.

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A. M. Almassri, H. W. Wan, S. A. Ahmad, S. Shafie, C. Wada, and K. Horio. 6th International Symposium on Sensor Science and 4th SPINTECH Technology Thesis Award (I3S2018), Abstract acceptance, “Wearable robotic glove for hand rehabilitation based on real time pressure measurement system” Kenting, Taiwan, August 2018.

A. M. Almassri, H. W. Wan, S. A. Ahmad, S. Shafie, C. Wada, and K. Horio. The 6th Symposium on Applied Engineering and Sciences (SAES 2018), " Development of Real-time Secured Grasping System for Wearable Robotic Hand Glove," Kyutech, JAPAN, December 2018.