UNIVERSITI PUTRA MALAYSIA

DESIGN AND DEVELOPMENT OF PROTOTYPE ROBOT GRIPPER FOR OBJECT WEIGHT MEASUREMENT

AHMED M. M. ALMASSRI

FK 2015 138

DESIGN AND DEVELOPMENT OF PROTOTYPE ROBOT GRIPPER FOR OBJECT WEIGHT MEASUREMENT

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 Master of Science

December, 2014

DEDICATION

First and foremost, I would like to thank God, my creator, for giving me the intellectual capacity to learn about His creation. Without His gift and grace to me, I could do nothing. I dedicate my thesis work to my loving parents, **ROWAIDA** and **BADEE**, whose words of encouragement and push for tenacity ring in my ears. In addition, a special feeling of gratitude to my loving brothers, Ashraf, Hassan, Hani for supporting entire my life, as long as I was a child. I also dedicate this grateful work to my loving brother's sons, Ali and Badee, whose motivate me to complete my research efficiently I would like to express my utmost appreciation to my sister, **Isrra** without her encouragement I would never have started and without her support I never would have finished. Last but not least, I would like to thank my loving wife, **Asmaa**, for always being encouraging and supporting.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

DESIGN AND DEVELOPMENT OF PROTOTYPE ROBOT GRIPPER FOR OBJECT WEIGHT MEASUREMENT

By

AHMED MOHAMMED BADEE ALMASSRI

December 2014

Chairman: Associate Professor Wan Zuha B Wan Hasan, PhD

Faculty: Engineering

Robotic gripper is a mechatronic machine that is made to complete tasks whenever it is required, especially for repetitive and dangerous tasks as well as specific applications, such as military robots, automotive industries and medical operations. Such mentioned tasks, require a lot of labor force for the assembly line and material handling. Therefore, there is a significant need to have a dedicated machine, which is suitable for this application as a safety concern. This is difficult to be obtained without equipping the robotic gripper with some types of sensors. A few technologies have been used different types of sensors in order to measure the forces between the claw of robotic gripper and an object. A good example is a pressure sensor, which is commonly used in the robotic gripper operations, especially to grasp any object. However, the existing robotic gripper has never been introduced the weight measurement method while grasping object based on piezoresistive pressure sensor. In this research, many works are focused to overcome the weaknesses in the current design applications such as the pressure distribution for active area of robotic gripper, sensor type and specific pressure range of sensor. Therefore, this study has proposed a robotic gripper prototype with a new configuration of pressure sensor distribution, based on development of grasping algorithm for object's weight measurement. The new configuration of pressure sensors will be based on the proposed modified Wheatstone Bridge Circuit WBC as it has a high sensitivity as well as capability for grasping mechanism and weight measurement. The proposed work also includes the development of new algorithm for data extraction and signal conditioning analysis that will be loaded into the microcontroller system. Three circuits are designed and implemented in this research to investigate the pressure distribution and sensitivity output, including Traditional Pressure Sensor Circuit (TPSC), WBC type 1, and modified WBC type 2. In addition, a robotic gripper prototype has been developed for the experimental purposes of this study for the interface between pressure sensors and microcontroller system. As a result, a new approach of pressure sensor distribution on the robotic gripper prototype has been developed with proposed modified WBC and grasping algorithm with 0.982 sensitivity and 98.4% efficiency. Along with the new features of this prototype system, the combination of grasping and weight measurement is significantly improved when it is compared with the existing one.

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

MEREKABENTUK DAN MEMBANGUN PROTOTAIP ROBOT PENGGENGGAM UNTUK PENGUKURAN BERAT OBJEK

Oleh

AHMED MOHAMMED BADEE ALMASSRI

Disember 2014

Pengerusi: Professor Madya Wan Zuha B Wan Hasan, PhD

Fakulti: Kejuruteraan

Penggenggam robotik adalah mesin mekatronik yang dicipta untuk menyelesaikan tugasan setiap kali ia diperlukan, terutama untuk tugas-tugas yang berulang-ulang dan berbahaya serta aplikasi khas seperti robot untuk kegunaan ketenteraan, industri automotif dan juga perubatan. Tugasan tersebut memerlukan tenaga buruh yang banyak untuk barisan pemasangan dan pengendalian material. Oleh kerana itu, bagi mengutamakan faktor keselamatan, sesbuah mesin hendaklah dikhususkan mengikut kesesuain penggunaanya. Ini adalah sukar untuk diperolehi tanpa melengkapkan penggenggam robotik dengan beberapa jenis penderia. Terdapat beberapa teknologi yang telah digunakan untuk mengukur daya pada penyepit penggenggan robotik dan sesebuah objek dengan menggunakan pelbagai jenis penderia. Antara contoh yang baik adalah dengan menggunakan penderia tekanan, ianya biasa digunakan untuk memegang apa-apa objek pada robot penggenggam Walaubagaimanapun penggenggam robotik yang sedia ada tidak pernah lagi diperkenalkan dengan kaedah pengukuran berat sambil menggenggam sesebuah objek berdasarkan penderia tekanan *piezoresistive*. Dalam kajian ini, pelbagai usaha telah dijalankan dengan memberi tumpuan untuk mengatasi kelemahan-kelemahan dalam rekaan sedia ada seperti taburan tekanan untuk kawasan aktif pada penggenggam robotik, jenis penderia dan juga julat tekanan khusus untuk penderia tersebut.Oleh itu, kajian ini telah mencadangkan sebuah prototaip penggenggam robotik dengan tatarajah pengagihan penderia tekanan baharu, berdasarkan pembangunan algoritma genggaman dengan mengukur berat objek tersebut. Konfigurasi baharu mengenai penderia tekanan ini akan berdasarkan kepada cadangan *Wheatstone Bridge Circuit* WBC yang telah diubahsuai, ini kerana ianya mempunyai sensitiviti yang tinggi dan juga keupayaan untuk menggenggam dan mengukur berat pada sesuatu objek. Kajian ini juga merangkumi pembangunan algortima baharu untuk mengekstak data dan juga menganilis isyarat yang akan dimuat naik ke dalam system mikropengawal. Tiga litar elektronik telah direka bentuk dan digunakan dalam kajian ini bagi menyiasat taburan tekanan dan kepekaan keluaran, iaitu *Traditional Pressure Sensor Circuit* (TPSC), WBC jenis 1, and WBC jenis 2 yang telah diubah suai. Di samping itu, sebuah prototaip robot penggenggam telah dibangunkan untuk menjalankan uji kaji dalam kajian ini dengan menjadi pengntara muka diantara penderia tekanan dengan system mikropengawal. Hasilnya, prototaip robot penggenggam telah dibangunkan menggunakan WBC yang telah diubahsuai seperti yang telah dicadangkan dan juga algoritma genggaman yang menggunakan pendekatan pengagihan penderia tekanan yang baharu dengan kepekaan 0.982 dan kecekapan 98.%. Kesimpulannya, ciri-ciri baharu penggabungan mekanisma genggaman dengan pengukuran berat objek pada sistem prototaip ini menampakkan penambahbaikkan dengan sangat baik jika dibandingkan dengan yang telah sedia ada.

ACKNOWLEDGEMENTS

In the Name of God, Most Gracious, Most Merciful

No one walks alone on the journey of life. I wish to thank my committee members who were more than generous with their expertise and precious time. A special thanks to Assoc. Prof. Dr. Wan Zuha bin Wan Hasan, my committee chairman for his countless hours of reflecting, reading, encouraging, and most of all patience throughout the entire process. Thank you Dr, Siti Anom Binti Ahmad, Dr. Asnor Juraiza binti Ishak and Assoc. Prof. Dr. Chikamune Wada for agreeing to serve on my committee. Besides, I would like to thank Faculty of Engineering and the Institute of Advanced Technology of University Putra of Malaysia which provided me a good environment and equipment in successfully completing this project.
Furthermore, I am indebted to my parents, Badee and Rowaida, for inculcating in me the dedication and discipline to do whatever I undertake well. I cannot thank my brothers, Ashraf, Hassan, Hani, Azeez and Youssof enough for their selfless effort to support me. Also, I would like to thanks again my dear Israa, for her love, kindness and support she will remain in my heart all the time. Last but not least, I would like to appreciate my friends Abdullah, Hisham, Naem, Shanab, Nedal, Okal, Saed, Asem for their editorial support.

I certify that a Thesis Examination Committee has met on 12 December 2014 to conduct the final examination of Ahmed M. M. Almassri on his thesis entitled "Design and Development of Prototype Robot Gripper for Object Weight Measurement" 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.

Members of the Thesis Examination Committee were as follows:

Mohd Khair bin Hassan, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohammad Hamiruce Marhaban, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Azura binti Che Soh, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Farrukh Nagi, PhD
Associate Professor
Universiti Tenaga Nasional
Jalan Ikram-Uniten
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 26 February 2015

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

Wan Zuha bin Wan Hasan, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Siti Anom binti Ahmad, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Asnor Juraiza binti Ishak, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Chikamune Wada, PhD
Associate Professor
Graduate School of Life Science and System Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: _________________

Name and Matric No: ____

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____________________
Name of Chairman of Supervisory Committee: ____________________

Signature: ____________________
Name of Chairman of Supervisory Committee: ____________________

Signature: ____________________
Name of Chairman of Supervisory Committee: ____________________

Signature: ____________________
Name of Chairman of Supervisory Committee: ____________________

TABLE OF CONTENTS

		Page
ABSTRACT		i
ABSTRAKT		ii
ACKNOWLEDGEMENTS		iv
APPROVAL		v
DECLARATION		vii
LISTS OF TABLES		xi
LIST OF FIGURES		xii
LIST OF ABBREVIATIONS		xvi
CHAPTER		1
1	**INTRODUCTION**	1
	1.1 Overview	1
	1.2 Problem Statement	2
	1.3 Research Objectives	2
	1.4 Research Scope	3
	1.5 Thesis Layout	4
	1.6 Summary	5
2	**LITERATURE REVIEW**	6
	2.1 Introduction	6
	2.2 Pressure Sensor	7
	2.2.1 Tactile Pressure Sensor	7
	2.3 Force Sensor	9
	2.3.1 Force Sensor Based on Transduction Methods	9
	2.3.2 Piezoresistive Flexiforce Sensor	11
	2.3.3 Piezoresistive Polymer Material	12
	2.4 Basic concept of Wheatstone Bridge Circuit (WBC)	13
	2.4.1 Significance of WBC	14
	2.4.2 Modifications and Applications of WBC	14
	2.5 Robotic Gripper Theory and Applications	18
	2.5.1 Robotic Gripper System	18
	2.5.2 Tactile Pressure Sensors - Transduction Techniques and Applications	21
	2.5.3 Grasping Applications	25
	2.6 Controllers	28
	2.6.1 Microcontroller System	28
	2.7 Summary	30
3	**METHODOLOGY**	31
	3.1 Introduction	31
	3.2 Overview of Research Methodology	32
	3.3 Design Concept of Robotic Gripper	35
	3.3.1 System Requirements for the Proposed Robotic Gripper Prototype	38
	3.4 The Operation of Robotic Gripper Prototype	38
	3.4.1 Movement calibration	40

		3.4.2 Sensors distribution for grasping the object	41
		3.4.3 Signal conditioning and data extraction of grasping object	44
	3.5	Pressure distribution based on Traditional pressure sensor circuit (TPSC)	47
		3.5.1 Analog readout circuit based on the TPSC	49
	3.6	Pressure distribution based on the proposed modified WBC	51
		3.6.1 Analog readout circuit based on the proposed modified WBC type 2	53
	3.7	The Proposed Algorithm of Robotic Gripper for grasping an object and measuring its weight	55
	3.8	Summary	58
4	**RESULTS AND DISCUSSION**		59
	4.1	Overview	59
	4.2	Robotic Gripper	59
		4.2.1 Robotic Gripper Development	60
		4.2.2 Distribution of the Pressure Sensors	60
	4.3	Experimental Results of Robotic Gripper System	61
		4.3.1 Experimental Results based on TPSC	62
		4.3.2 Experimental results based on the Modified WBC type 1	69
		4.3.3 Experimental Results based on the Proposed Modified WBC type 2	76
	4.4	Comparison	85
	4.5	Summary	87
5	**CONCLUSIONS AND RECOMMENDATIONS**		88
	5.1	Conclusions	88
	5.2	Recommendations	88
REFERENCES			90
APPENDICES			98
	APPENDIX A		100
	APPENDIX B		104
	APPENDIX C		113
BIODATA OF STUDENT			121
LIST OF PUBLICATIONS			121

LISTS OF TABLES

Table **Page**

2.1. Relative merits and demerits of various pressure sensor types 10

2.2. Pressure Sensor with Various Applications Based on Different Transduction Methods 23

3.1. The released components for Robotic Gripper application 34

3.2. The Specifications of Prototype Robotic Gripper 37

3.3. The Specifications of DC Servo Motor 39

3.4. Piezoresistive pressure sensor specifications 43

4.1. Results of measurement output Data of sample object based on TPSC 64

4.2. Results of measurement output Data of sample object based on TPSC 65

4.3. Results of measurement output Data of sample object based on the Modified WBC type1 71

4.4. Results of measuring the output Data of sample object based on the Proposed modified WBC type 2 77

4.5. Results of measuring the output data of sample object based on the Proposed modified WBC type 78

4.6. Experimental Results between the three methods based on the Robotic Gripper protot 86

LIST OF FIGURES

Figure		Page
2.1.	Structure of a Tactile pressure sensor	8
2.2.	Scanning electronic of pressure sensor	8
2.3.	Piezoresistive Tactile Pressure Sensor	11
2.4.	Components of FlexiForce sensors	12
2.5.	Sensor design with thin Polymer membrane	13
2.6.	The Schematic diagram of standard Wheatstone bridge circuit	13
2.7.	Wheatstone Bridge in IC Technology	15
2.8.	Wheatstone Bridge with piezoresistive pressure transducers	16
2.9.	(a) Piezoresistive sensor (b) Piezoresistive in a WBC	16
2.10.	A modified Wheatstone bridge circuit	17
2.11	Types of Robotic Arm	18
2.12.	Robot Arm design configurations	19
2.13.	Robotic Gripper with Tactile pressure sensors	20
2.14.	Optical Three-Axis Tactile sensors	20
2.15.	Robot Gripper with pressure sensors	20
2.16.	Robotic Grasping device with multi-force sensing at base of fingers	26
2.17.	Compliance control using external Force/Torque sensors.	27
2.18.	The Shadow Dexterous Robot Hand	28
2.19.	Microcontroller Applications	29
3.1.	Flowchart of the Project's Methodology	31
3.2.	Block diagram of the Proposed Robotic Gripper system	32
3.3.	Block diagram of Feedback System for Grasping Mechanism	33
3.4.	The Robotic Gripper Prototype	35
3.5.	The Robotic Gripper Prototype equipped with sensors	36

3.6. The Robotic Gripper components. (a) The Base (b) The Frame (c) The claw (d) The Carrier 36

3.7. Block diagram of the sensors and controller system 38

3.8. The actuator components. (a) Servo motor controller (b) DC servo motor 39

3.9. Block diagram of connection MCU and servo motor controller for control of the movement calibration 40

3.10. Pulse width (a) The Pulse of servo motor (b) The Position of servo motor corresponding to the width of pulses 41

3.11. The distribution of pressure sensors on the right and left claw of the Robotic Gripper Prototype 42

3.12. Piezoresistive Pressure Sensor 42

3.13. Experimental setup of pressure sensor.(a) Setup of the sensing area (b) Setup of the pressure sensor for conditioning purpose 45

3.14. Typical response of Resistance/Conductance versus Force 45

3.15. Typical response of Voltage versus Force 46

3.16. Schematic diagram of the Robotic Gripper prototype connection based on the TPSC 47

3.17. Schematic diagram of inverting op-amp with pressure sensor 48

3.18. Schematic diagram of the analog readout circuit based on the TPSC 49

3.19. Schematic diagram of implemented PCB of analog readout circuit based on the TPSC 50

3.20. Schematic diagram of the Robotic Gripper prototype connection based on the proposed modified WBC 51

3.21. Schematic diagram of the modified WBC type 1 52

3.22. Schematic diagram of the proposed modified WBC type 2 54

3.23. Schematic diagram of implemented PCB of analog readout circuit based on the proposed modified WBC type 2 54

3.24. Experimental set up of adjusting the distance of IR sensor on the Robotic Gripper prototype 55

3.25. Flowchart of the proposed grasping algorithm for measuring the weight of an object with a Robotic Gripper 57

4.1. The Experimental setup for the Robotic Gripper prototype 59

4.2. The Proposed Robotic Gripper Prototype 60

4.3. Pressure sensors distribution on the Robotic Gripper Prototype 61

4.4. Selected Sample object for experiment 61

4.5. Experimental setup of Robotic Gripper Prototype based on TPSC 62

4.6. The developed PCB based on TPSC 63

4.7. Output Voltage versus Pressure based on the TPSC (a) The total pressure output over a series of weights (b) The pressure distribution of sample calibrated output over a series of weights 66

4.8. Output Resistance/Conductance versus Pressure over a series of weights 68

4.9. The Duty Cycle Output on different positions of DC servo motor over a series of weights 68

4.10. Experimental setup of Robotic Gripper prototype based on the modified WBC type 1 69

4.11. The developed PCB based on the proposed modified WBC 70

4.12. Output Voltage versus Pressure based on the modified WBC type 1 (a) The total pressure output over a series of weights (b)The pressure distribution of sample calibrated output over a series of weights 73

4.13. Output Resistance/Conductance versus Pressure over a series of weights 74

4.14. The Duty Cycle output on different positions of DC servo motor over a series of weights 75

4.15. Time response of the pressure sensor output based on modified WBC type 1 (a) Time response of 50g object (b) Time response of 200g object 75

4.16. Output Voltage versus Pressure based on the Proposed modified WBC type 2 (a) The total pressure output over a series of weights (b) The Pressure distribution of sample calibrated output over a series of weights 80

4.17. Output Resistance/Conductance versus Pressure over a series of weights 81

4.18. The Duty Cycle Output on different positions of DC servo moto over a series of weights 81

4.19. Time response for 85g object based on the Proposed modified WBC type 2 82

4.20. Time response for 220g object based on Proposed modified WB type 2 83

4.21. Output Voltage versus Weight based on the proposed modified WBC type 2 84

4.22. Comparison between the three methods for investigation of the Sensitivity 85

LIST OF ABBREVIATIONS

WBC	Wheatstone Bridge Circuit
TPSC	Traditional Pressure Sensor Circuit
PPM	Part Per Million
IC	Integrated Circuit
DDC	Direct Digital Converter
MEMS	Microelectromechanical Systems
RFID	Radio Frequency Identification
PPS	Pressure Profile Systems
SCARA	Self-Compliance Automatic Robot
PID	Proportional Integral Derivative
GMC	Generic Model Control
MCU	Microcontroller
PIC	Programmable Interface Controller
JAL	Just Another Language
IR	Infrared Sensor
LCD	Liquid Crystal Display
DC	Direct current
RC	Radio Control
DOF	Degree Of Freedom
PWM	Pulse Width Modulation
UART	Universal Asynchronous Receiver and Transmitter
TTL	Transistor-Transistor Logic
ICSP	In Circuit Serial Programming
FSR	Force Sensing Resistor
CPU	Central Processing Unit
PCB	Printed Circuit Board
ABS	Acrylonitrile Butadiene Styrene
3D	Three Dimension
USB	Universal Serial Bus
avg	Average
sum	Summation
Max	Maximum

CHAPTER 1

INTRODUCTION

1.1 Overview

Human beings have long recognized the significant importance of robots, especially the robotic manipulators such as robotic hand or robotic gripper. Day by day, the robotic gripper becomes more important, according to the fact that robots involve with the environment, grasping objects, performing tasks or even emulating the human hand. Some types of robotic hands and grippers have been implemented for various purposes such as dexterous manipulation [1, 2], artificial limbs[3], grasping the objects [4, 5], and pick and place application [6]. The function of grasping mechanism based on robotic gripper system has been the purpose of many researchers [7, 8]. They have dedicated their concern to a physical touch and interface between the robotic gripper and objects, during the handling process [9, 10]. In addition, they have developed miscellaneous types of grippers equipped with pressure sensors that can perform special tasks or even unfamiliar grasping objects [11-15]. Accordingly, there are many types of pressure sensors that have been utilized for grasping objects based on different principles, such as resistive, capacitive, optical, ultrasonic, magnetic, piezoresistive, and piezoelectric sensors. Tactile piezoresistive pressure sensor is considered as one of the appropriate pressure sensors, used to grab, hold and handle objects with accurate feedback information about the objects.

However, the performance of robotic gripper system based on pressure sensors during the grasping process still has some weaknesses in determining the pressure distribution and defining the pressure range as well as the sensitivity output of signal conditioning. Moreover, the existing robotic gripper has never addressed the weight measurement method while holding the unknown object. Hence, many techniques and apparatuses have been sophisticated based on pressure sensors to overcome these deficiencies, but none of them used the piezoresistive pressure sensor based on proposed modified Wheatstone Bridge Circuit WBC.

In this research, the proposed robotic gripper prototype with a new configuration of pressure sensors distribution based on the modified WBC type 1 has been designed and developed for grasping an object and measuring its weight. This circuit has been used to enhance the pressure measurement and increase the sensitivity output of the pressure sensor. Along with the configuration of pressure sensors on the claw of the robotic gripper prototype, a modified WBC type 2 is also utilized to increase the detection surface area to provide more measurement. Besides, a grasping algorithm system is applied based on programmable interface controller (PIC) for secure grasp, object's weight measurement as well as extraction and analysing the signal output. This research definitely has the potential of producing a new robotic gripper prototype system, which incorporates specific pressure force and robust system and complies with an object's weight.

1.2 Problem Statement

The control system of robot gripper has been developed and investigated for different applications. It has been reported that the robot gripper executes a particular task of grasping the object. Nevertheless, the weight measurement method while grasping object has not found yet in the current robotic gripper applications. In addition, some problems have been appeared in this research, including pressure distribution for active area of robotic gripper, sensor type and specific pressure range of sensor [16, 17]. Other disputes such as hysteresis and drift that may cause erroneous reading have emerged [18]. Furthermore, the robot gripper faces some problems in having proper contact points to hold the specific object and this may distort the required posture while the robot gripper is holding the object [19].

Besides the above mentioned weaknesses of the existing robot gripper system for grasping the objects, there is no piezoresistive pressure sensor assembled on the claw of robotic gripper. Therefore, this will be a motive to design and develop a new approach of pressure sensor distribution on the robotic gripper prototype based on proposed algorithm for object's weight measurement. The new features of a prototype robotic gripper system can improve the combination of grasping and weight measurement compared to the existing one. In addition, it can calibrate and evaluate the data that needs to be processed. One recently related work is a robotic grasping device with multi-force sensing at base of fingers is still not used the force sensors on the claw of the robot [20]. In this study, piezoresistive pressure sensor type has been investigated according to a proposed modified Wheatstone Bridge Circuit (WBC) in order to implement the research works, because the outcome of this research is supposed to have a high sensitivity. In addition, it needs to be suitable for robot's grasping mechanism.This new configuration of pressure sensors, which has been based on the modified WBC, will improve the measurement output with increasing the sensitivity output as well as the detection surface area to provide more measurement. This process is useful for achieving a successful operation and compact grasping action and extract accurate data for the signal outputs.

1.3 Research Objectives

The aim of this research is to design and perform a new approach of pressure sensor distribution on the robotic gripper prototype based on a proposed modified Wheatstone Bridge Circuit (WBC) as well as a proposed algorithm while covering the weaknesses in the previous works. The main objectives of this research are:

i. To develop a prototype robot gripper system for grasping solid object with extra features of weight measurement based on pressure forces.

ii. To assemble a new configuration of multiple pressure sensors based on modified Wheatstone Bridge Circuit (WBC) for obtaining high sensitivity and efficient pressure distribution.

iii. To apply a new grasping algorithm flow to enhance the data extraction and signal conditioning of the outputs of multiple sensors.

1.4 Research Scope

This research focuses on the design of the robotic gripper prototype as well as development of grasping algorithm for measuring the weight of objects. In addition, the robotic gripper prototype has small dimensions (170mm x 150mm x 160mm). It has one claw with 86.5mm x 2.5mm x 45mm dimensions, which is also designed to be able to hold a small object. Furthermore, the robotic gripper prototype can open with 50mm maximum width and the claw can move in x-axis only. The maximum object's weight that the robotic gripper will be able to hold is 600g. Besides, it has one joint with one mini servo motor. The flexibility and simplicity are the key features of this robotic gripper prototype.

In this project, the researcher also focuses on a hard object with rectangular shape as a sample to be grasped. This selected object is also flat and the dimensions are larger than the entire claw of the robotic gripper prototype to ensure that all pressure sensors touch the object. In addition, four pressure sensors are used and assembled on the claw of the robotic gripper prototype. The type of selected sensor is a piezoresistive FlexiForce sensor. It has three ranges of force, but according to the current design, the selected force is 0-25 lbs, which is used to measure the pressure between the robotic gripper and the selected object. The sensing area of pressure sensor is 9.35mm in diameter and the sensor is ultra-thin with 0.208mm thickness. The operating temperature is -9°C to 60°C.

Additionally, two driver controller circuits are selected to be used in this project; SC08A for servo motor driver and SK40C for PIC MCU. Both of these driver controller circuits are aligned and incorporated with other components with high compatibility in order to achieve the objectives of this research as required. Besides, three circuits are designed and implemented in this research using the electronic components, which have reliable performance and are available at low cost. These circuits are based on three methods, including the modified WBC type 1, modified WBC type 2, and TPSC.

1.5 Thesis Layout

This thesis is organized into five chapters. The first chapter introduces the overview of robotic gripper prototype for grasping mechanism and includes concise information about the performance of the robotic gripper system based on pressure sensor technique that implies the current proposed design. The problem statement in this project is presented in the next section of this chapter. This initiated the research to overcome the current problem by developing a robotic gripper prototype with new features. 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 two last sections of this chapter.

The second chapter presents the literature review related to the research. Different techniques of measuring force and interface pressure between the robotic gripper and objects are presented. Then the chapter focuses on the concept of a WBC and its modifications that are devoted to measuring various types of resistances with high sensitivity. Besides, the literature studies have also discussed the related research of force sensor based on various types of transduction methods. Then, this chapter offers a related robotic gripper system applications based on tactile pressure sensor with different transduction methods and the control algorithm of grasping objects. Finally, the controller part is presented as one of the main component parts of the robotic gripper system.

The third chapter illustrates the applied methodology for this research to develop a robotic gripper prototype, equipped with piezoresistive pressure sensors based on a modified WBC. In the first main section of this chapter, the developed robotic gripper prototype and its operations are explained. After that, the pressure sensor distribution and signal conditioning for extracting the data are demonstrated. The next two sections describe the comparison between three circuits for pressure distribution to grasp the object and measure its weight. The analog readout circuit for three techniques are designed and implemented. Lastly, the proposed algorithm, which is based on the robotic gripper system for automatic grasped object is presented as well as all required components to reach the objectives of this project.

The fourth chapter focuses on the analysis of experimental results and discussions of the robotic gripper prototype system. This encompasses the illustration of the robotic gripper prototype development and the distribution of pressure sensors based on the proposed WBC. In addition, it describes the pressure distribution results of designing analog readout circuit based on the TPSC as well as the proposed WBC type 1 and WBC type 2.

Finally, the fifth chapter summarizes the overall outcome of proposed current research and recommendations for future work for robotic gripper grasping mechanism. The conclusion and future work are presented based on the proposed methodology as well as the achieved experimental results.

1.6 Summary

A comprehensive introduction to develop robotic gripper prototype system for grasping an object and measuring its weight has been described in the current chapter. 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. To complete this proposed method, a large number of investigations with lots of analysis are implemented so that the outcome of this research can overcome the obstacles.

REFERENCES

W.-C. Choi, "Polymer micromachined flexible tactile sensor for three-axial loads detection," Transactions on Electrical and Electronic Materials, vol. 11, pp. 130-133, 2010.

A. Rodriguez, M. T. Mason, and S. S. Srinivasa, "Manipulation capabilities with simple hands," in Experimental Robotics, 2014, pp. 285-299.

H.-K. Lee, J. Chung, S.-I. Chang, and E. Yoon, "Normal and shear force measurement using a flexible polymer tactile sensor with embedded multiple capacitors," Microelectromechanical Systems, Journal of, vol. 17, pp. 934-942, 2008.

L. C. Mizelmoe, "Gripper for objects," ed: Google Patents, 2012.

V. Lippiello, F. Ruggiero, B. Siciliano, and L. Villani, "Visual grasp planning for unknown objects using a multifingered robotic hand," Mechatronics, IEEE/ASME Transactions on, vol. 18, pp. 1050-1059, 2013.

Y. Zhang, B. K. Chen, X. Liu, and Y. Sun, "Autonomous robotic pick-and-place of microobjects," Robotics, IEEE Transactions on, vol. 26, pp. 200-207, 2010.

J. E. P. Puig, N. E. N. Rodriguez, and M. Ceccarelli, "A Methodology for the Design of Robotic Hands with Multiple Fingers," International Journal of Advanced Robotic Systems, vol. 5, 2008.

O. Penisi, M. Ceccarelli, and G. Carbone, "Classification of Mechanisms for Industrial Fingers With Two fingers," Iberoamerican Journal of Mechanical Engineering, vol. 7, pp. 59-75, 2003.

M. T. Mason and J. K. Salisbury Jr, Robot hands and the mechanics of manipulation: MIT press, 1985.

M. T. Ciocarlie and P. K. Allen, "Hand posture subspaces for dexterous robotic grasping," The International Journal of Robotics Research, vol. 28, pp. 851-867, 2009.

E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, and H. M. Jaeger, "Universal robotic gripper based on the jamming of granular material," Proceedings of the National Academy of Sciences, vol. 107, pp. 18809-18814, 2010.

A. Zaki, A. Soliman, O. Mahgoub, and A. El-Shafei, "Design and implementation of efficient intelligent robotic gripper," in Modelling, Identification and Control (ICMIC), The 2010 International Conference on, 2010, pp. 710-716.

R. Kouskouridas, A. Amanatiadis, and A. Gasteratos, "Guiding a robotic gripper by visual feedback for object manipulation tasks," in Mechatronics (ICM), 2011 IEEE International Conference on, 2011, pp. 433-438.

A. Maldonado, U. Klank, and M. Beetz, "Robotic grasping of unmodeled objects using time-of-flight range data and finger torque information," in Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on, 2010, pp. 2586-2591.

J. Bohg, M. Johnson-Roberson, B. León, J. Felip, X. Gratal, N. Bergstrom, D. Kragic, and A. Morales, "Mind the gap-robotic grasping under incomplete observation," in Robotics and Automation (ICRA), 2011 IEEE International Conference on, 2011, pp. 686-693.

J. Tegin and J. Wikander, "Tactile sensing in intelligent robotic manipulation–a review," Industrial Robot: An International Journal, vol. 32, pp. 64-70, 2005.

H. Kawasaki, T. Komatsu, and K. Uchiyama, "Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II," Mechatronics, IEEE/ASME Transactions on, vol. 7, pp. 296-303, 2002.

J. A. Fishel and G. E. Loeb, "Sensing tactile microvibrations with the BioTac—Comparison with human sensitivity," in Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on, 2012, pp. 1122-1127.

R. Platt, A. H. Fagg, and R. A. Grupen, "Extending fingertip grasping to whole body grasping," in Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on, 2003, pp. 2677-2682.

M. D. Summer, P. M. Bosscher, and L. J. Wilkinson, "Robotic grasping device with multi-force sensing at base of fingers," ed: Google Patents, 2013.

G. Hirzinger, K. Landzettel, B. Brunner, M. Fischer, C. Preusche, D. Reintsema, A. Albu-Schäffer, G. Schreiber, and B.-M. Steinmetz, "DLR's robotics technologies for on-orbit servicing," Advanced Robotics, vol. 18, pp. 139-174, 2004.

C. Lovchik and M. A. Diftler, "The robonaut hand: A dexterous robot hand for space," in Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on, 1999, pp. 907-912.

M. H. Lee and H. R. Nicholls, "Review Article Tactile sensing for mechatronics—a state of the art survey," Mechatronics, vol. 9, pp. 1-31, 1999.

T. B. Martin, R. O. Ambrose, M. A. Diftler, R. Platt Jr, and M. Butzer, "Tactile gloves for autonomous grasping with the NASA/DARPA Robonaut," in Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on, 2004, pp. 1713-1718.

C. Ashruf, "Thin flexible pressure sensors," Sensor Review, vol. 22, pp. 322-327, 2002.

G. S. Gupta, S. C. Mukhopadhyay, C. H. Messom, and S. N. Demidenko, "Master–slave control of a teleoperated anthropomorphic robotic arm with gripping force sensing," Instrumentation and Measurement, IEEE Transactions on, vol. 55, pp. 2136-2145, 2006.

M. Ferguson-Pell, S. Hagisawa, and D. Bain, "Evaluation of a sensor for low interface pressure applications," Medical engineering & physics, vol. 22, pp. 657-663, 2000.

P. S. Girão, O. Postolache, and J. M. D. Pereira, "Tactile sensors for robotic applications," Measurement, 2012.

A. S. Fiorillo, "Design and characterization of a PVDF ultrasonic range sensor," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, vol. 39, pp. 688-692, 1992.

A. M. ALmassri, W. WanHasan, S. Ahmad, A. Ishak, A. Ghazali, D. Talib1and, and C. WADA, "Pressure Sensor: State of Art, Design and Application for Robotic Hand."

D. E. Gyi, J. M. Porter, and N. K. Robertson, "Seat pressure measurement technologies: considerations for their evaluation," Applied Ergonomics, vol. 29, pp. 85-91, 1998.

X. Wu, S. Rakheja, and P.-E. Boileau, "Distribution of human–seat interface pressure on a soft automotive seat under vertical vibration," International Journal of Industrial Ergonomics, vol. 24, pp. 545-557, 1999.

F. Khoshnoud and C. W. de Silva, "Recent advances in MEMS sensor technology–biomedical applications," Instrumentation & Measurement Magazine, IEEE, vol. 15, pp. 8-14, 2012.

R. S. Dahiya and M. Valle, "Tactile sensing for robotic applications," Sensors, Focus on Tactile, Force and Stress Sensors, pp. 289-304, 2008.

H. Zhang and E. So, "Hybrid resistive tactile sensing," Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on, vol. 32, pp. 57-65, 2002.

A. M. Almassri, W. Hasan, S. A. Ahmad, and A. J. Ishak, "A sensitivity study of piezoresistive pressure sensor for robotic hand," in Micro and Nanoelectronics (RSM), 2013 IEEE Regional Symposium on, 2013, pp. 394-397.

A. J. Steckl, H. You, and D.-Y. Kim, "Flexible electrowetting and electrowetting on flexible substrates," in SPIE OPTO, 2011, pp. 795607-795607-6.

K. Myny, E. van Veenendaal, G. H. Gelinck, J. Genoe, W. Dehaene, and P. Heremans, "An 8-bit, 40-instructions-per-second organic microprocessor on plastic foil," Solid-State Circuits, IEEE Journal of, vol. 47, pp. 284-291, 2012.

A. A. Babar, J. Virtanen, V. Bhagavati, L. Ukkonen, A. Elsherbeni, P. Kallio, and L. Sydanheimo, "Inkjet-printable UHF RFID tag antenna on a flexible ceramic-polymer composite substrate," in Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International, 2012, pp. 1-3.

N. Saldanha and D. C. Malocha, "Pseudo-orthogonal frequency coded wireless SAW RFID temperature sensor tags," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, vol. 59, pp. 1750-1758, 2012.

N. Ferreira, T. Krah, A. Dietzel, S. Buttgenbach, A. S. Granada, and J. Garcia, "Micro sensors with polymer membrane for accurate 3D force and displacement measurements," in Sensors, 2013 IEEE, 2013, pp. 1-4.

H. Sasaki, H. Nishinaka, and K. Shida, "Automated measurement system for 1-Omega standard resistors using a modified Wheatstone bridge," in Precision Electromagnetic Measurements, 1990. CPEM'90 Digest., Conference on, 1990, pp. 122-123.

K. R. Baker and R. F. Dziuba, "Automated NBS 1-/g= W/Measurement System," Instrumentation and Measurement, IEEE Transactions on, vol. 32, pp. 154-158, 1983.

M. E. Cage, R. F. Dziuba, and B. Field, "A test of the quantum Hall effect as a resistance standard," Instrumentation and Measurement, IEEE Transactions on, vol. 34, pp. 301-303, 1985.

A. Hartland, R. G. Jones, B. P. Kibble, and D. J. Legg, "The relationship between the SI ohm, the ohm at NPL, and the quantized Hall resistance," Instrumentation and Measurement, IEEE Transactions on, vol. 1001, pp. 208-213, 1987.

H. Sasaki, H. Nishinaka, and K. Shida, "High-Precision Automated Resistance Measurement Using a Modified Wheatstone Bridge," in Precision Electromagnetic Measurements, 1988. CPEM 88 Digest. 1988 Conference on, 1988, pp. 157-157.

Y. H. Ghallab and W. Badawy, "A new design of a current-mode wheatstone bridge using operational floating current conveyor," in MEMS, NANO and Smart Systems, The 2006 International Conference on, 2006, pp. 41-44.

S. J. Azhari and H. Kaabi, "AZKA cell, the current-mode alternative of Wheatstone bridge," Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on, vol. 47, pp. 1277-1284, 2000.

P. R. Nagarajan, B. George, and V. J. Kumar, "Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai 600036, India," in Sensing

Technology (ICST), 2013 Seventh International Conference on, 2013, pp. 516-519.

H.-H. Tsai, C.-C. Hsieh, C.-W. Fan, Y.-C. Chen, and W.-T. Wu, "Design and characterization of temperature-robust piezoresistive micro-pressure sensor with double-Wheatstone-bridge structure," in Design, Test, Integration & Packaging of MEMS/MOEMS, 2009. MEMS/MOEMS'09. Symposium on, 2009, pp. 363-368.

I. Padron, A. T. Fiory, and N. M. Ravindra, "Integrated Optical and Electronic Pressure Sensor," Sensors Journal, IEEE, vol. 11, pp. 343-350, 2011.

C. S. Sander, J. W. Knutti, and J. D. Meindl, "A monolithic capacitive pressure sensor with pulse-period output," Electron Devices, IEEE Transactions on, vol. 27, pp. 927-930, 1980.

O. Brand, H. Baltes, and U. Baldenweg, "Ultrasound-transducer using membrane resonators realized with bipolar IC technology," in Micro Electro Mechanical Systems, 1994, MEMS'94, Proceedings, IEEE Workshop on, 1994, pp. 33-38.

L. Rufer, C. C. Domingues, S. Mir, V. Petrini, J.-C. Jeannot, and P. Delobelle, "A CMOS compatible ultrasonic transducer fabricated with deep reactive ion etching," Microelectromechanical Systems, Journal of, vol. 15, pp. 1766-1776, 2006.

T. A. Nunn and J. B. Angell, "An IC absolute pressure transducer with built-in reference chamber," in Indwelling and implantable pressure transducers: based on workshop held in Cleveland, Ohio on December 4 and 5, 1975, sponsored by the Biotechnology Resources Branch (RR-00857) and the National Institute of General Medical Sciences (GM-14267) of the National Institutes of Health, 1977, p. 133.

A. Gieles and G. Somers, "Miniature pressure transducers with a silicon diaphragm," Philips technical review, vol. 33, pp. 14-20, 1973.

S. Jacobsen, E. Iversen, D. Knutti, R. Johnson, and K. Biggers, "Design of the Utah/MIT dextrous hand," in Robotics and Automation. Proceedings. 1986 IEEE International Conference on, 1986, pp. 1520-1532.

F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, and C. Melchiorri, "UBH 3: an anthropomorphic hand with simplified endo-skeletal structure and soft continuous fingerpads," in Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on, 2004, pp. 4736-4741.

J. Butterfaß, M. Grebenstein, H. Liu, and G. Hirzinger, "DLR-Hand II: Next generation of a dextrous robot hand," in Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on, 2001, pp. 109-114.

A. Kargov, T. Asfour, C. Pylatiuk, R. Oberle, H. Klosek, S. Schulz, K. Regenstein, G. Bretthauer, and R. Dillmann, "Development of an anthropomorphic hand for a mobile assistive robot," in Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on, 2005, pp. 182-186.

C. Jones, G. Ross, J. Hewit, and A. Slade, "Robotic sorting of paper items from a random pile," Mechatronics, vol. 10, pp. 869-880, 2000.

Y. Ma, Z. Cao, X. Dong, C. Zhou, and M. Tan, "A multi-robot coordinated hunting strategy with dynamic alliance," in Control and Decision Conference, 2009. CCDC'09. Chinese, 2009, pp. 2338-2342.

A. Ryberg, M. Ericsson, A.-K. Christiansson, K. Eriksson, J. Nilsson, and M. Larsson, "Stereo vision for path correction in off-line programmed robot welding," in Industrial Technology (ICIT), 2010 IEEE International Conference on, 2010, pp. 1700-1705.

M. Ali, R. Puffer, and H. Roman, "Evaluation of a multifingered robot hand for nuclear power plant operations and maintenance tasks," Technical Paper-Society of Manufacturing Engineers. MS., 1994.

G. Song, H. Wang, J. Zhang, and T. Meng, "Automatic docking system for recharging home surveillance robots," Consumer Electronics, IEEE Transactions on, vol. 57, pp. 428-435, 2011.

J. M. Romano, K. Hsiao, G. Niemeyer, S. Chitta, and K. J. Kuchenbecker, "Human-inspired robotic grasp control with tactile sensing," Robotics, IEEE Transactions on, vol. 27, pp. 1067-1079, 2011.

H. Yussof, J. Wada, and M. Ohka, "Sensorization of robotic hand using optical three-axis tactile sensor: Evaluation with grasping and twisting motions," Journal of Computer Science, vol. 6, p. 955, 2010.

C. C. Kemp, A. Edsinger, and E. Torres-Jara, "Challenges for robot manipulation in human environments," IEEE Robotics and Automation Magazine, vol. 14, p. 20, 2007.

M. T. Mason and J. K. Salisbury Jr, "Robot hands and the mechanics of manipulation," 1985.

R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing—from humans to humanoids," Robotics, IEEE Transactions on, vol. 26, pp. 1-20, 2010.

K. Kim, K. Lee, Y. Kim, D. Lee, N. Cho, W.-H. Kim, K.-B. Park, H. Park, Y. Park, and J. Kim, "3-axes flexible tactile sensor fabricated by Si micromachining and packaging technology," in Micro Electro Mechanical Systems, 2006. MEMS 2006 Istanbul. 19th IEEE International Conference on, 2006, pp. 678-681.

T.-R. Hsu, MEMS & Microsystems: Design, Manufacture, and Nanoscale Engineering: John Wiley & Sons, 2008.

M. Asadnia, A. Kottapalli, Z. Shen, J. Miao, and M. Triantafyllou, "Flexible and surface-mountable piezoelectric sensor arrays for underwater sensing in marine vehicles," 2013.

A. Aqilah, A. Jaffar, S. Bahari, C. Low, and T. Koch, "Resistivity characteristics of single miniature tactile sensing element based on pressure sensitive conductive rubber sheet," in Signal Processing and its Applications (CSPA), 2012 IEEE 8th International Colloquium on, 2012, pp. 223-227.

K. Noda, Y. Hashimoto, Y. Tanaka, and I. Shimoyama, "MEMS on robot applications," in Solid-State Sensors, Actuators and Microsystems Conference, 2009. TRANSDUCERS 2009. International, 2009, pp. 2176-2181.

H. Takao, K. Sawada, and M. Ishida, "Monolithic silicon smart tactile image sensor with integrated strain sensor array on pneumatically swollen single-diaphragm structure," Electron Devices, IEEE Transactions on, vol. 53, pp. 1250-1259, 2006.

J. H. Shan, T. Mei, L. Sun, L. Ni, M. Meng, and J. R. Chu, "The design and fabrication of a flexible three-dimensional force sensor skin," in Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on, 2005, pp. 1818-1823.

B. J. Kane, M. R. Cutkosky, and G. T. Kovacs, "A traction stress sensor array for use in high-resolution robotic tactile imaging," Microelectromechanical Systems, Journal of, vol. 9, pp. 425-434, 2000.

P. Rey, P. Charvet, M. Delaye, and S. Abou Hassan, "A high density capacitive pressure sensor array for fingerprint sensor application," in Solid State Sensors and Actuators, 1997. TRANSDUCERS'97 Chicago., 1997 International Conference on, 1997, pp. 1453-1456.

M. Monta, N. Kondo, and Y. Shibano, "Agricultural robot in grape production system," in Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on, 1995, pp. 2504-2509.

H. Kiba, Y. Itoh, and K. Kiryu, "Vehicle body painting robot," ed: Google Patents, 1985.

H.-S. Kang, J. Suh, and S. J. Kwak, "Welding on the Fly by using Laser Scanner and Robot," in Control, Automation and Systems (ICCAS), 2011 11th International Conference on, 2011, pp. 1688-1691.

H.-S. Kang, J. Suh, and T.-D. Cho, "Study on robot application technology for laser welding," in Smart Manufacturing Application, 2008. ICSMA 2008. International Conference on, 2008, pp. 354-356.

R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," Nature Reviews Neuroscience, vol. 10, pp. 345-359, 2009.

T. Valency and M. Zacksenhouse, "Instantaneous model impedance control for robots," in Intelligent Robots and Systems, 2000.(IROS 2000). Proceedings. 2000 IEEE/RSJ International Conference on, 2000, pp. 757-762.

C.-C. Cheah and D. Wang, "Learning impedance control for robotic manipulators," Robotics and Automation, IEEE Transactions on, vol. 14, pp. 452-465, 1998.

T. Tan, M. Ang, and C. Teo, "Non-model-based impedance control of an industrial robot," in Advanced Robotics, 1997. ICAR'97. Proceedings., 8th International Conference on, 1997, pp. 407-412.

R. Ozawa, S. Arimoto, S. Nakamura, and J.-H. Bae, "Control of an object with parallel surfaces by a pair of finger robots without object sensing," Robotics, IEEE Transactions on, vol. 21, pp. 965-976, 2005.

D. Johansen, D. B. Popovic, and L. N. A. Struijk, "Control of robotic and prosthetic arms using an inductive tongue control system," in Replace, Repair, Restore, Relieve–Bridging Clinical and Engineering Solutions in Neurorehabilitation, ed: Springer, 2014, pp. 863-865.

F. Ficuciello, "Modelling and Control for Soft Finger Manipulation and Human-Robot Interaction," Università degli studi di Napoli Federico II, 2010.

J. Jo, S.-K. Kim, Y. Oh, and S.-R. Oh, "Compliance control of a position controlled robotic hand using F/T sensors," in Ubiquitous Robots and Ambient Intelligence (URAI), 2011 8th International Conference on, 2011, pp. 446-450.

J. Jo, S.-K. Kim, Y. Oh, and S.-R. Oh, "Contact force control of a robotic hand using F/T sensory feedback with a rigid object," in Automation Science and Engineering (CASE), 2012 IEEE International Conference on, 2012, pp. 436-441.

R. H. Cannon and E. Schmitz, "Initial experiments on the end-point control of a flexible one-link robot," The International Journal of Robotics Research, vol. 3, pp. 62-75, 1984.

G. Hastings and W. Book, "Verification of a linear dynamic model for flexible robotic manipulators," in Robotics and Automation. Proceedings. 1986 IEEE International Conference on, 1986, pp. 1024-1029.

A. Bernardino, M. Henriques, N. Hendrich, and J. Zhang, "Precision grasp synergies for dexterous robotic hands," in Robotics and Biomimetics (ROBIO), 2013 IEEE International Conference on, 2013, pp. 62-67.

M. Ogino, I. Tsukinoki, K. Hosoda, and M. Asada, "Controlling lateral stepping of a biped robot by swinging torso toward energy efficient walking," in Intelligent

Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on, 2004, pp. 1359-1364.

O. H. H. Hyötyniemi, "SIMULATION TOOL OF A BIPED WALKING ROBOT MODEL," ed: Helsinki University of Technology Control Engineering Laboratory, 2004.

N. Aziz, M. Hussain, and I. Mujtaba, "Performance of different types of controllers in tracking optimal temperature profiles in batch reactors," Computers & Chemical Engineering, vol. 24, pp. 1069-1075, 2000.

S. Karacan, H. Hapoğlu, and M. Alpbaz, "Multivariable system identification and generic model control of a laboratory scale packed distillation column," Applied thermal engineering, vol. 27, pp. 1017-1028, 2007.

C. Torres, J. de Jesús Rubio, C. F. Aguilar-Ibáñez, and J. H. Pérez-Cruz, "Stable optimal control applied to a cylindrical robotic arm," Neural Computing and Applications, vol. 24, pp. 937-944, 2014.

D. J. Braun, F. Petit, F. Huber, S. Haddadin, P. Van Der Smagt, A. Albu-Schaffer, and S. Vijayakumar, "Robots driven by compliant actuators: Optimal control under actuation constraints," 2013.

K. S. Al-Olimat and A. A. Ghandakly, "Multiple model reference adaptive control algorithm using on-line fuzzy logic adjustment and its application to robotic manipulators," in Industry Applications Conference, 2002. 37th IAS Annual Meeting. Conference Record of the, 2002, pp. 1463-1466.

K. B. Pimenta, J. M. Rosário, and D. Dumur, "Application of direct adaptive generalized predictive control (GPCAD) to a robotic joint," in Industrial Electronics, 2003. ISIE'03. 2003 IEEE International Symposium on, 2003, pp. 1011-1016.

M. Hidalgo, G. Tene, and A. Sánchez Terán, "Fuzzy control of a robotic arm using EMG signals," 2007.