



**UNIVERSITI PUTRA MALAYSIA**

**A NEURAL NETWORK SOLUTION TO SINGULAR CONFIGURATION IN  
TRAJECTORY TRACKING OF A SERIAL ROBOT**

**ALI T. HASAN**

**FK 2009 56**



**A NEURAL NETWORK SOLUTION TO SINGULAR CONFIGURATION  
IN TRAJECTORY TRACKING OF A SERIAL ROBOT**

**By  
ALI T. HASAN**

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

**September 2009**



# DEDICATION

A Special Dedication To  
My Family



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

**A NEURAL NETWORK SOLUTION TO SINGULAR CONFIGURATION IN  
TRAJECTORY TRACKING OF A SERIAL ROBOT**

By

**ALI T. HASAN**

**September 2009**

**Chairman: Associate Professor Napsiah Ismail, PhD**

**Faculty: Engineering**

Singularities and uncertainties in arm configurations are the main problems in kinematics of serial robots. The complexity in the solution arises from robots geometry and non-linear equations (trigonometric equations) occur when transforming between Cartesian and joint spaces where multiple solutions and singularities exist. Mathematical solutions for the problem may not always correspond to the physical solution and methods of solution depend on the robot configuration.

In this research, a trajectory tracking approach is proposed for a 6 Degrees Of Freedom (DOF) serial robot manipulator. The proposed solution is carried out through two stages. First the kinematics model of the Fanuc *M710i* robot was solved using the D-H method to show the exact location of singular



configurations of the robot, and then Artificial Neural Networks (ANNs) are trained to overcome these arising problems. Solving the Inverse Kinematics (IK) of serial manipulators by using ANNs has two problems, one of these is the selection of the appropriate configuration of the network and the other is the generating of suitable training data sets.

In this research, although this is very difficult in practice, training data were recorded experimentally from sensors fixed on each joint to overcome the effect of kinematics uncertainties presence in the real world such as ill-defined linkage parameters, links flexibility and backlashes in gear train. Off-line training was implemented for the experimentally obtained training data.

Two networks configurations from the literature were tested and developed following the recommendations of the original authors, then compared to find the best configuration to be used. First the effect of orientation of the tool was examined (as one of the networks does not considered the effect of orientation while the other network does), and then the effect of the Jacobian matrix to the solution for the both configurations was examined.

Performance comparison shows that when the effect of the orientation of the tool was considered in the solution with the Jacobian matrix effect, better results in terms of precision and iteration during training the ANN were obtained.

The effect of the network architecture was also examined in order to find the best network configuration to solve the problem. A network with all the parameters considered together in one network has been compared to six different networks, where the parameters of every joint were considered independently. Results obtained show that having one network considering all the problem's parameters together give a better response than using 6 different networks representing the parameters of each joint apart from other joints.

The resultant network with the best configuration was tested experimentally using new different set of data that has never been introduced to the network before, this data set was meant to pass through the singular configurations, in order to show the generality and efficiency of the proposed approach.

Experimental trajectory tracking has shown the ability of the proposed Artificial Neural Networks approach to overcome the disadvantages of using some schemes like the Fuzzy Learning Control for example that only remembers the most recent data sets introduced, as the literature has shown.

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

**PENYELESAIAN RANGUAIAN NEURAL UNTUK TATARAJAH SINGULARITI  
BAGI PENJEJAKAN TRAJEKTORI ROBOT SERIAL**

Oleh

**ALI T. HASAN**

**September 2009**

**Pengerusi: Prof. Madya Datin Napsiah Ismail, PhD**

**Fakulti: Kejuruteraan**

Singulariti dan ketidakpastian dalam konfigurasi lengan adalah masalah utama dalam kinematik robot bersiri. Kerumitan dalam penyelesaian timbul daripada geometri robot dan persamaan taksekata (persamaan trigonometri) terjadi apabila perubahan antara satah Kartesian dan ruang sambungan di mana penyelesaian berbilang dan singulariti wujud. Penyelesaian matematik untuk masalah ini mungkin tidak selalunya selaras dengan penyelesaian fizik dan kaedah-kaedah penyelesaian bergantung pada konfigurasi robot.

Dalam penyelidikan ini, satu pendekatan penjejakan trajektori telah dicadangkan bagi enam darjah kebebasan pergerakan (DOF) pengolah robot bersiri. Penyelesaian yang dicadangkan dijalankan dengan dua peringkat. Pertama model kinematik robot Fanuc *M710i* diperolehi menggunakan kaedah D-H untuk



menunjukkan lokasi sebenar konfigurasi singular robot, dan kemudian Rangkaian Neuro Buatan (ANNs) telah dilatih bagi mengatasi masalah yang muncul.

Menyelesaikan kinematik songsang (IK) pemutar belit bersiri dengan menggunakan ANNs mempunyai dua masalah, satu daripadanya adalah pemilihan konfigurasi rangkaian yang padan dan yang lain ialah penjanaan set-set data latihan yang sesuai.

Dalam penyelidikan ini, data latihan telah direkodkan secara eksperimen daripada pengesan yang ditetapkan pada setiap sendi untuk mengatasi kesan ketidakpastian kinematik yang hadir di dalam dunia sebenar seperti parameter rangkaian yang tidak ditakrif dengan baik, hubungan kelonggaran dan tendangan dalam gear latihan. Latihan luar talian telah dilaksanakan secara eksperimen untuk memperoleh data latihan.

Dua konfigurasi rangkaian daripada pembacaan telah diuji dan dibangunkan mengikut cadangan penyelidik asal, kemudiannya dibandingkan bagi mencari konfigurasi terbaik untuk digunakan. Pertama, kesan orientasi alat telah diperiksa, dan kemudian kesan matriks Jacobian untuk penyelesaian bagi kedua-dua konfigurasi juga telah diperiksa.

Perbandingan prestasi menunjukkan bahawa apabila kesan orientasi alat dipertimbangkan dalam penyelesaian dengan kesan matriks Jacobian,



keputusan lebih baik dari segi ketepatan dan lelaran semasa latihan ANN dialami.

Kesan seni bina rangkaian telah juga diperiksa bagi tujuan mencari konfigurasi rangkaian yang terbaik untuk menyelesaikan masalah. Satu rangkaian dengan semua parameter dianggap bersama dalam satu rangkaian telah dibandingkan dengan enam rangkaian berbeza, di mana parameter bagi setiap sendi dianggap secara bebas. Keputusan yang diperolehi menunjukkan bahawa mempunyai satu rangkaian dengan mempertimbangkan kesemua parameter masalah bersama menunjukkan gerak balas yang lebih baik daripada menggunakan enam rangkaian berbeza yang mewakili parameter bagi setiap sendi yang bersendirian.

Rangkaian yang dihasilkan dengan konfigurasi terbaik telah diuji secara eksperimen dengan menggunakan tiga set data baru berbeza yang tidak pernah diperkenalkan kepada rangkaian sebelum ini, set data ini telah ditetapkan untuk melalui konfigurasi singular, dengan tujuan untuk menunjukkan keluasan makna dan kecekapan bagi pendekatan yang telah dicadangkan.

Eksperimen penjejakan trajektori telah menunjukkan keupayaan pendekatan Rangkaian Neuro Buatan cadangan untuk mengatasi kelemahan dalam menggunakan skema-skema seperti kawalan pengajaran Fuzzy contohnya yang hanya mengingat set data yang paling mutakhir diperkenalkan, seperti yang ditunjukkan dalam pembacaan.

## ACKNOWLEDGMENTS

First of all, Great thanks to the Most Gracious and Most Merciful **ALLAH** (S.W.T) for the help of which this work would not have been possible without.

I wish to express my profound appreciation and sincere gratitude to the chairman of the supervisory committee, Associate Professor Datin Dr. Napsiah Ismail for her kind assistance, support, advice, encouragement, and suggestions throughout this work and during the preparation of this thesis.

Furthermore, I would like to take this opportunity to forward my deepest appreciation and gratitude to supervisory committee members Associate Professor Dr. Ishak Aris, Associate Professor Dr. Mohammad Hamiruce Marhaban and Professor Dr. A.M.S. Hamouda, I am grateful for their willingness to serve on my supervisory committee, constant encouragement, helpful advice and fruitful discussions.

Thanks and acknowledgements are meaningless if not extended to my parents who deserve my deepest appreciation. I am grateful for the countless sacrifices they made to ensure that I could pursue my PhD, and for always being there for me. Real and deepest thanks to them (May **ALLAH** (S.W.T) bless and protect them and may live long and healthy). All praise and thanks words said to them will not be enough.



A particular note of thanks is also given to Miss Normalina Jamaluddin, the science officer of the Spatial and Numerical Modeling Lab. (ITMA), and, also to Mr. Muhamad Saufi Mohd Kassim and Mrs. Rosiah Osman the science officers of the Intelligent Systems and Robotics Lab. (ITMA), for their assistance in providing the necessary tools to perform this work.

I would like to express my appreciation and thanks to all who have taught me during my life. Lastly but not least, very very special thanks to my brothers and sister for their love, support and encouragement



I certify that a Thesis Examination Committee has met on the 29<sup>th</sup> of September 2009 to conduct the final examination of Ali T. Hasan on his thesis entitled " A Neural Network Solution To Singular Configuration In Trajectory Tracking of A Serial Robot " 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.

Members of the Thesis Examination Committee were as follows:

**Nor Mariah Adam, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Wan Ishak Wan Ismail, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Tang Sai Hong, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Zahari Taha, PhD**

Professor  
Faculty of Engineering  
Universiti Malaya  
(External Examiner)

---

**BUJANG KIM HUAT, PhD**

Professor and Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:



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:

**Napsiah Ismail, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Ishak Aris, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Mohammad Hamiruce Marhaban, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**A.M.S. Hamouda, PhD**

Professor  
Faculty of Engineering  
University of Qatar  
(Member)

---

**HASANAH MOHD GHAZALI, PhD**

Professor and Dean  
School of Graduate Studies  
University Putra Malaysia

Date:

## DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

---

**ALI T. HASAN**

Date:

## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	vi
<b>ACKNOWLEDGEMENTS</b>	ix
<b>APPROVAL</b>	xi
<b>DECLARATION</b>	xiii
<b>LIST OF TABLES</b>	xvi
<b>LIST OF FIGURES</b>	xvii
<b>LIST OF ABBREVIATIONS</b>	xxviii
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	
1.1 Problem Statement	7
1.2 Research's Objectives	8
1.3 Scope of the Research	8
1.4 Importance of the Study	10
1.5 Thesis Layout	11
<b>2 LITERATURE REVIEW</b>	
2.1 Analytical Approach	12
2.1.1 Position Analysis	13
2.1.2 Velocity Analysis	16
2.2 Intelligent Approach	25
2.3 Summary	48
<b>3 METHODOLOGY</b>	
3.1 Analytical Solution	55
3.1.1 Position Analysis	56
3.1.2 Velocity Analysis	62
3.2 Artificial Neural Networks Solution	66
3.2.1 Obtaining Data Sets	67
3.2.2 Artificial Neural Networks' Design	71
3.3 Summary	77
<b>4 ANALYTICAL APPROACH</b>	
4.1 Position Analysis of the FANUC $M - 710i$ Robot	78
4.1.1 Forward Kinematics	80
4.1.2 Inverse Kinematics	83
4.2 Jacobian Analysis	90
4.2.1 Singularity Analysis	95
4.2.2 Singular Configuration of the FANUC $M - 710i$ Manipulator	96
4.3 Summary	98



<b>5</b>	<b>ARTIFICIAL NEURAL NETWORKS APPROACH</b>	
5.1	Training Phase	100
5.1.1	The Effect of Orientation	101
5.1.2	The Effect of the Jacobian Matrix	114
5.1.3	The Effect of The Network Architecture	140
5.2	Testing Phase	157
5.2.1	First Testing Set	158
5.2.2	Second Testing Set	172
5.2.3	Third Testing Set	186
5.3	Discussion	200
<b>6</b>	<b>CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK</b>	
6.1	Conclusions	214
6.2	Recommendations for Future Research	217
	<b>REFERENCES</b>	218
	<b>APPENDICES</b>	227
	<b>BIODATA OF STUDENT</b>	267
	<b>LIST OF PUBLICATIONS</b>	268





## LIST OF TABLES

Table		Page
4.1	D-H parameters of the Fanuc $M - 710i$ manipulator	80
5.1	Total error percentages of the 3 - 6 Network Configuration compared to the 6 - 6 Network Configuration	109
5.2	Error percentages obtained during training of the 4 – 12 Network Configuration	114
5.3	Experimental trajectory tracking error percentages for the 3-6 Network Configuration compared to the 4-12 Network Configuration	116
5.4	Error percentages obtained during training of the 7 – 12 Network configuration	119
5.5	Experimental trajectory tracking error percentages for the 6-6 Network Configuration compared to the 7-12 Network Configuration	121
5.6	Training error percentages for the 4-12 Network Configuration compared to the 7-12 Network Configuration	132
5.7	Training error percentages for the 7-12 Network Configuration compared to the 7-2 Network Configuration	149
5.8	Experimental error percentages for the testing data set for each joint for the first testing set	164
5.9	Experimental error percentages of the testing trajectory for the first testing set	165
5.10	Experimental error percentages for the testing data set for each joint for the second testing set	172
5.11	Experimental error percentages of the testing trajectory for the second testing set	179
5.12	Experimental error percentages for the testing data set for each joint for the third testing set	186
5.13	Experimental error percentages of the testing trajectory for the third testing set	193



## LIST OF FIGURES

Figure		Page
1.1	The Fanuc <i>M – 710i</i> Robot	9
2.1	A schematic diagram of the implemented system by Köker et al. [36]	26
2.2	The kinematics model of the manipulator used by Köker et al. showing its direct kinematics equations	27
2.3	The two network configurations used by Hasan et al. [31]	28
2.4	The learning curve of Joint number 3 as a sample of the research done by Hasan et al. [31]	29
2.5	The network used in Bingul's et al. study [34]	30
2.6	Learning curves for the three networks used by köker [29]	32
2.7	The two networks used in Karlik's study [5]	34
2.8	The original network and its adjoint used in Kuroe's study [35]	36
3.1	The general description of the adopted methodology	54
3.2	Analytical solution flow chart	55
3.3	Position analysis steps flow chart	56
3.4	Flow chart for the Artificial Neural Networks solution methodology	66
3.5	The Teach Pendent	70
3.6	Teach pendent screen shows how Cartesian position; orientation and joint angles are shown	70
3.7	Teach pendent screen shows how feed rates and position data are shows on the display screen	71
3.8	The Training Process	72
3.9	Training Stage I	74
3.10	Training Stage II	76
4.1	D-H Coordinate system for the Fanuc <i>M – 710i</i> Robot	79



4.2	Hand coordinate system and wrist coordinate system	84
4.3	Two different arm configurations corresponding to the two solutions of $\theta_3$	87
4.4	Screw coordinates with respect to an instantaneous reference frame for the Fanuc $M - 710i$ robot	90
5.1	The architecture of the 3-6 Network Configuration	102
5.2	The learning curves for the 3-6 Network Configuration	103
5.3	The architecture of the 6-6 Network Configuration	104
5.4	Learning curves for the 6-6 Network Configuration	105
5.5	Learning curve of joint 1 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	106
5.6	Learning curve of joint 2 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	107
5.7	Learning curve of joint 3 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	107
5.8	Learning curve of joint 4 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	108
5.9	Learning curve of joint 5 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	108
5.10	Learning curve of joint 6 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	109
5.11	Angular position tracking of Joint 1 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	110
5.12	Angular position tracking of Joint 2 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	111
5.13	Angular position tracking of Joint 3 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	111
5.14	Angular position tracking of Joint 4 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	111



5.15	Angular position tracking of Joint 5 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	112
5.16	Angular position tracking of Joint 6 for the 3-6 Network Configuration compared to the 6-6 Network Configuration	113
5.17	The architecture of the 4 – 12 Network Configuration	115
5.18	The learning curve for the 4 – 12 Network Configuration	115
5.19	Experimental Trajectory tracking of the X Coordinate for the 3-6 Network Configuration compared to the 4-12 Network Configuration	117
5.20	Experimental Trajectory tracking of the Y Coordinate for the 3-6 Network Configuration compared to the 4-12 Network Configuration	117
5.21	Experimental Trajectory tracking of the Z Coordinate for the 3-6 Network Configuration compared to the 4-12 Network Configuration	118
5.22	The architecture of the 7 – 12 Network Configuration	119
5.23	Learning curve for the 7 – 12 Network Configuration	120
5.24	Experimental trajectory tracking of the X Coordinate for the 6-6 Network Configuration compared to the 7-12 Network Configuration	122
5.25	Experimental trajectory tracking of the Y Coordinate for the 6-6 Network Configuration compared to the 7-12 Network Configuration	122
5.26	Experimental trajectory tracking of the Z Coordinate for the 6-6 Network Configuration compared to the 7-12 Network Configuration	123
5.27	Experimental trajectory tracking of the Roll orientation angle for the 6-6 Network Configuration compared to the 7-12 Network Configuration	123
5.28	Experimental trajectory tracking of the Pitch orientation angle for the 6-6 Network Configuration compared to the 7-12 Network Configuration	124



5.29	Experimental trajectory tracking of the Yaw orientation angle for the 6-6 Network Configuration compared to the 7-12 Network Configuration	124
5.30	Learning curve of the angular position of joint 1 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	125
5.31	Learning curve of the angular position of joint 2 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	126
5.32	Learning curve of the angular position of joint 3 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	126
5.33	Learning curve of the angular position of joint 4 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	127
5.34	Learning curve of the angular position of joint 5 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	127
5.35	Learning curve of the angular position of joint 6 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	128
5.36	Learning curve of the angular velocity of joint 1 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	128
5.37	Learning curve of the angular velocity of joint 2 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	129
5.38	Learning curve of the angular velocity of joint 3 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	129
5.39	Learning curve of the angular velocity of joint 4 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	130
5.40	Learning curve of the angular velocity of joint 5 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	130



5.41	Learning curve of the angular velocity of joint 6 for the 4-12 Network Configuration compared to the 7-12 Network Configuration	131
5.42	Angular position tracking of joint 1 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	133
5.43	Angular position tracking of joint 2 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	134
5.44	Angular position tracking of joint 3 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	134
5.45	Angular position tracking of joint 4 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	135
5.46	Angular position tracking of joint 5 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	135
5.47	Angular position tracking of joint 6 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	136
5.48	Angular velocity tracking of joint 1 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	136
5.49	Angular velocity tracking of joint 2 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	137
5.50	Angular velocity tracking of joint 3 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	137
5.51	Angular velocity tracking of joint 4 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	138
5.52	Angular velocity tracking of joint 5 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	138
5.53	Angular velocity tracking of joint 6 for the 7-12 Network Configuration compared to the 4-12 Network Configuration	139
5.54	The architecture of the 7 –2 Network Configuration	141
5.55	Learning curve of angular position of joint 1 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	142



5.56	Learning curve of angular position of joint 2 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	143
5.57	Learning curve of angular position of joint 3 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	143
5.58	Learning curve of angular position of joint 4 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	144
5.59	Learning curve of angular position of joint 5 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	144
5.60	Learning curve of angular position of joint 6 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	145
5.61	Learning curve of angular velocity of joint 1 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	145
5.62	Learning curve of angular velocity of joint 2 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	146
5.63	Learning curve of angular velocity of joint 3 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	146
5.64	Learning curve of angular velocity of joint 4 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	147
5.65	Learning curve of angular velocity of joint 5 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	147
5.66	Learning curve of angular velocity of joint 6 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	148
5.67	Angular position tracking of joint 1 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	150



5.68	Angular position tracking of joint 2 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	151
5.69	Angular position tracking of joint 3 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	151
5.70	Angular position tracking of joint 4 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	152
5.71	Angular position tracking of joint 5 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	152
5.72	Angular position tracking of joint 6 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	153
5.73	Angular velocity tracking of joint 1 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	153
5.74	Angular velocity tracking of joint 2 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	154
5.75	Angular velocity tracking of joint 3 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	154
5.76	Angular velocity tracking of joint 4 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	155
5.77	Angular velocity tracking of joint 5 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	155
5.78	Angular velocity tracking of joint 6 for the 7-12 Network Configuration compared to the 7-2 Network Configuration	156
5.79	Predicted angular position experimental tracking of joint 1 for the first testing set	158
5.80	Predicted angular position experimental tracking of joint 2 for the first testing set	159
5.81	Predicted angular position experimental tracking of joint 3 for the first testing set	159
5.82	Predicted angular position experimental tracking of joint 4 for the first testing set	160
5.83	Predicted angular position experimental tracking of joint 5 for the first testing set	160





5.84	Predicted angular position experimental tracking of joint 6 for the first testing set	161
5.85	Predicted angular velocity experimental tracking of joint 1 for the first testing set	161
5.86	Predicted angular velocity experimental tracking of joint 2 for the first testing set	162
5.87	Predicted angular velocity experimental tracking of joint 3 for the first testing set	162
5.88	Predicted angular velocity experimental tracking of joint 4 for the first testing set	163
5.89	Predicted angular velocity experimental tracking of joint 5 for the first testing set	163
5.90	Predicted angular velocity experimental tracking of joint 6 for the first testing set	164
5.91	Predicted trajectory tracking of X Coordinate for the first testing set	166
5.92	Predicted trajectory tracking of Y Coordinate for the first testing set	167
5.93	Predicted trajectory tracking of Z Coordinate for the first testing set	168
5.94	Predicted trajectory tracking of Roll orientation angle for the first testing set	169
5.95	Predicted trajectory tracking of Pitch orientation angle for the first testing set	170
5.96	Predicted trajectory tracking of Yaw orientation angle for the first testing set	171
5.97	Predicted angular position experimental tracking of joint 1 for the second testing set	173
5.98	Predicted angular position experimental tracking of joint 2 for the second testing set	173
5.99	Predicted angular position experimental tracking of joint 3 for the second testing set	174

