

**DEVELOPMENT OF AN ADAPTIVE NEURO-
CONTROLLER AND SATELLITE SIMULATOR
FOR NANO-SATELLITE ATTITUDE CONTROL
SYSTEM**

SITI MARYAM BINTI SHARUN

© This item is protected by original copyright

UNIVERSITI MALAYSIA PERLIS

2013



UniMAP

© This item is protected by original copyright

UNIVERSITI MALAYSIA PERLIS

DECLARATION OF THESIS

Author's full name : SITI MARYAM BT SHARUN
Date of birth : 27TH JANUARY 1972
Title : DEVELOPMENT OF AN ADAPTIVE NEURO-CONTROLLER AND
SATELLITE SIMULATOR FOR NANO-SATELLITE ATTITUDE
CONTROL SYSTEM
Academic Session : 2008 - 2012

I hereby declare that the thesis becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This thesis is classified as :

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*
- RESTRICTED** (Contains restricted information as specified by the organization where research was done)*
- OPEN ACCESS** I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this thesis in whole or in part for the purpose of research or academic exchange only (except during a period of _____ years, if so requested above).

Certified by:

SIGNATURE

SIGNATURE OF SUPERVISOR

720127025260

(NEW IC NO. / PASSPORT NO.)

PROF. DR. MOHD YUSOFF MASHOR

NAME OF SUPERVISOR

NOTES : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful. First and foremost, I would like to thank Allah s.w.t for giving me the strengths and His blessing in completing this thesis. Alhamdulillah, all praises to Allah. Special appreciation goes to my supervisor, Prof. Dr. Mohd Yusoff Mashor for providing me the knowledge and whom never failed and stops giving me support from the beginning until the end which makes this research possible to be completed. His guidance and motivations always keep me focused on the objective of the research and choosing the right way in accomplishing it. Not forgetting a big appreciation towards my second supervisor, Prof. Dr. Sazali bin Yaacob for all the support in terms of knowledge, advice and streaming motivation during this period which help to keep my faith solid as ever.

I would also like to convey my gratitude to the Ministry of Higher Education (MOHE), for the scholarship as well as Astronautic Technology (M) Sdn. Bhd. (ATSB) for providing the information and constructive guidance during the research study. I would like to express my deepest gratitude to my beloved husband, mother and my sons, and the rest of my family for the prayer, love, motivation and encouragement that inspire me to strive harder for achieving the dreams.

Last but not least, I would like to thank InnoSAT team members especially Wan Nurhadani, Norhayati, Anis and Zul Azfar. My fellow friends, especially to Nadiatun, Hazlyna, Rafikha, Khusairi, Aimi and everyone that involves in this research directly and indirectly. Your help and encouragement really means to me. Thank you very much.

*To my beloved parents,
Sharun Ibrahim &
Che Gayah Mat Taib*

*My lovely husband,
Suhairi Mohamed*

*&
My sons,*

Muhammad Sufi

Muhammad Isa

Muhammad Aliff

Muhammad Muaz

Muhammad Aqil

*And last but not least
To all my family members*

TABLE OF CONTENTS

	PAGE
THESIS DECLARATION	i
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iv
LIST OF TABLES	x
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xx
LIST OF SYMBOLS	xxiv
ABSTRAK	xxix
ABSTRACT	xxx
CHAPTER 1 INTRODUCTION	
1.1 Introduction	1
1.2 Problem Statement	4
1.3 State-of-the-art	6
1.4 Research Objective	8
1.5 Scope of Research	9
1.6 Thesis Outline	11
CHAPTER 2 LITERATURE REVIEW	
2.1 Introduction	14
2.2 Small Satellite	15

2.2.1	Cube SAT	17
2.2.2	Innovative Satellite (InnoSAT)	20
2.3	Satellite Attitude Control System	22
2.3.1	Spin Stabilization	24
2.3.1.1	Single Spin	25
2.3.1.2	Dual Spin	25
2.3.2	Three-Axis-Stabilization	26
2.3.2.1	Magnetic Control	27
2.3.2.2	Wheels	28
2.3.2.3	Thrusters	29
2.3.3	Passive Control	31
2.3.3.1	Gravity Gradient	32
2.3.3.2	Passive Magnetic	34
2.3.4	Magnetic Torques and Magnetometer	35
2.4	Artificial Neural Network	36
2.4.1	Types of ANN	38
2.4.2	Application of ANN in Control System	44
2.4.3	Application of ANN in Satellite Attitude Control	47
2.5	Previous Work of Satellite Attitude Control	48
2.5.1	Intelligent Adaptive Controller	49
2.5.2	Conventional Controller	52
2.6	Hardware-In-Loop Satellite Simulator	55
2.7	Summary	59

CHAPTER 3 MATHEMATICAL MODELLING OF INNOVATIVE SATELLITE

3.1	Introduction	62
3.2	Coordinate Reference Frames	64
3.2.1	The Inertial Frame	65
3.2.2	The Orbital Frame	65
3.2.3	The Body Frame	66
3.3	Angular Momentum and the Inertia Matrix	67
3.3.1	Principal Axes of Inertia	71
3.3.2	Euler's Moment Equations	72
3.4	Attitude Kinematics Equations of Motion	72
3.4.1	Angular Velocity Vector of a Rotating Frame	73
3.4.2	Angular Velocities for the Transformation	74
3.5	Attitude Dynamics Equations of Motion	76
3.5.1	Equations of Motions for Satellite Attitude	77
3.5.2	Gravity Gradient Moment	78
3.5.3	Linearized Attitude Dynamics	83
3.6	Gravity Gradient Attitude Control	85
3.6.1	Purely Passive Control Method	86
3.6.2	Simulation Result of Purely Passive Control Method	90
3.7	Active Control Method	97
3.7.1	Active Control Method with small Euler angle	98
3.7.2	Active Control Method with Gravity Gradient	100

	Torque	
	3.7.3 Active Control Method with Coupling Factor	101
	3.8 Summary	102
CHAPTER 4	INTELLIGENT CONTROLLER FOR SATELLITE ATTITUDE CONTROL	
	4.1 Introduction	104
	4.2 Adaptive Neuro-Controller	105
	4.2.1 Control Scheme	108
	4.2.2 Controller Structure	114
	4.2.2.1 Multi Layered Perceptron (MLP) Network	115
	4.2.2.2 Hybrid Multi Layered Perceptron (HMLP) Network	116
	4.2.3 Estimation Algorithm	122
	4.2.4 Performance Analysis of ANC based on MLP and HMLP network	127
	4.3 Modified PID Controller	131
	4.4 Adaptive Parametric Black Box (APBB) controller	133
	4.5 The simulation for Y-Thompson Spin Rate Data	135
	4.6 Simulation Result of Active Control method for InnoSAT plant with small Euler angle	139
	4.6.1 Performance comparison between MLP, HMLP, APBB and MPID controller using step input and square wave input data	143
	4.6.2 Performance comparison between MLP, HMLP, APBB and MPID controller using step input and square wave input data	165

	HMLP, APBB and MPID controller using Y- Thompson spin rate data.	
4.7	Simulation Result of Active Control method for InnoSAT plant with Gravity Gradient (GG) Torque	168
4.7.1	Performance comparison between ANC and MPID controller using step input and square wave input data	169
4.7.2	Simulation result for ANC controller using Y- Thompson spin rate data.	170
4.8	Simulation Result of Active Control method for InnoSAT plant with Cross Coupling Factor	182
4.9	Conclusion	191
CHAPTER 5	PLUG AND PLAY InnoSAT ACS SIMULATOR	
5.1	Introduction	193
5.2	Previous work of Attitude Control Satellite Simulator	194
5.3	Satellite Simulator Development for InnoSAT ACS system	196
5.4	Requirements for ACS and Microcontroller	199
5.5	Microcontroller Specification and Assessment	202
5.5.1	Comparison between RCM3400 and RCM4100	205
5.5.2	Floating-Point Value Storage	206
5.6	Memory Management and Allocation	208
5.7	Hardware-In-Loop-Simulation Technique	211

5.7.1	Requirements	213
5.7.2	MCU and Computer Interface	214
5.7.3	Real Time Simulation	218
5.8	Result and Discussion for InnoSAT ACS Simulator	219
5.8.1	Comparison Result of HILS and MATLAB simulation for InnoSAT plant with small Euler angle	221
5.8.2	Comparison Result of HILS and MATLAB simulation for InnoSAT plant with GG Torque	233
5.8.3	Comparison Result of HILS and MATLAB simulation for InnoSAT plant with Cross Coupling Factor	245
5.8.4	Comparison Result of HILS and MATLAB simulation for InnoSAT plant using Y-Thompson spin rate data.	257
5.9	Conclusions	261
CHAPTER 6 CONCLUSIONS AND FUTURE WORK		
6.1	Conclusions	263
6.2	Research Contributions	265
6.3	Recommendations for Future Work	266
REFERENCES		268
APPENDICES		282
LIST OF PUBLICATIONS		305

LIST OF TABLES

NO.		PAGE
2.1	Satellite categorization with respect to mass	17
3.1	Summary of stability conditions in terms of principal moments of inertia	90
3.2	Satellite Characteristics and Initial Conditions for InnoSAT	91
3.3	InnoSAT Characteristics and Initial Conditions for Active Control Method	99
4.1	Analysis of hidden nodes numbers using ANC based on MLP network for InnoSAT plant with small Euler angle	127
4.2	Analysis of hidden nodes numbers using ANC based on HMLP network for InnoSAT plant with small Euler angle	129
4.3	The Step Response Analysis of MLP, HMLP, MPID and APBB controllers for Roll Axis	145
4.4	The Step Response Analysis of MLP, HMLP, MPID and APBB controllers for Pitch Axis	146
4.5	The Step Response Analysis of MLP, HMLP, MPID and APBB controllers for Yaw Axis	146
4.6	MSE for MLP, HMLP, PID and APBB controllers with unity gain	149
4.7	MSE for MLP, HMLP, PID and APBB controller with varying gain	152
4.8	MSE for MLP, HMLP, PID and APBB controller with measurement noise	154
4.9	MSE for MLP, HMLP, PID and APBB controller with one sample time delay	157

4.10	MSE for MLP, HMLP, PID and APBB controller with all conditions	159
4.11	MSE for MLP, HMLP, PID and APBB controller with step disturbance	162
4.12	Best controller performance analysis for InnoSAT Euler model based on time response	163
4.13	Best controller performance analysis for InnoSAT Euler model based on Mean Square Error (MSE)	164
4.14	MSE for MLP, HMLP, MPID and APBB controller with Y-Thompson data	166
4.15	The Step Response Analysis of ANC and MPID controllers for Roll Axis	169
4.16	Step Response Analysis of ANC and MPID controllers for Pitch Axis	169
4.17	The Step Response Analysis of ANC and MPID controllers for Yaw Axis	169
5.1	Comparison Features of Rabbit 3000 and Rabbit 4000	204
5.2	IEEE 754-2008 internal floating an double representation	206
5.3	Time response analysis for ANC with 3 input and ANC with 8 input	220
5.4	MSE of Simulation and HILS with step input	223
5.5	MSE of Simulation and HILS with square wave input	225
5.6	MSE of Simulation and HILS with varying gain	228
5.7	MSE of Simulation and HILS with measurement noise	230
5.8	MSE of Simulation and HILS with step disturbance	233
5.9	MSE of Simulation and HILS for GG model with step input	236
5.10	MSE of Simulation and HILS for GG model with square wave input	238
5.11	MSE of Simulation and HILS for GG model with varying gain	240

5.12	MSE of Simulation and HILS for GG model with measurement noise	242
5.13	MSE of Simulation and HILS for GG model with step disturbance	244
5.14	MSE of Simulation and HILS for cross coupling with step input	248
5.15	MSE of Simulation and HILS for cross coupling with square wave input	251
5.16	MSE of Simulation and HILS with for cross coupling with varying gain	253
5.17	MSE of Simulation and HILS for cross coupling with measurement noise	255
5.18	MSE of Simulation and HILS for cross coupling with step disturbance	257
5.19	MSE of Simulation and HILS for Y-Thompson input	260
A.1	Satellite Characteristics and Initial Conditions for TiungSAT- 1(Micro-satellite)	283

LIST OF FIGURES

NO.		PAGE
1.1	Block diagram of satellite sub-systems	2
1.2	Block diagram of satellite control	9
1.3	Block diagram of satellite attitude control system	10
2.1	(a) Original design of an off the shelf CubeSAT development-Kit, (b) 3D image of the CubeSAT with label that used for simulation in STK, (c) Exploded view of CubeSAT 3D Object.	18
2.2	Poly Pico-satellite Orbital Deployer(P-POD) and cross section	19
2.3	External view of InnoSAT showing main external components with coordinate system	21
2.4	Block Diagram of Attitude Determination and Control System	23
2.5	Example of feed-forward neural network	39
2.6	Example of feed-back neural network	42
2.7	The new EPOS facility: (a) robotics-based testbed and (b) operation station	59
3.1	Satellite and desired orbital frame	65
3.2	Definition of the orbit reference frame	67
3.3	Angular motion of a rigid body	70
3.4	Gravitational moments on an Asymmetric Satellite	79
3.5	Stability and instability regions for GG-stabilized satellites	89
3.6	Roll angle response of InnoSAT	94
3.7	Pitch angle response of InnoSAT	94
3.8	Yaw angle response of InnoSAT	95

3.9	Roll angle response of TiungSAT-1	96
3.10	Pitch angle response of TiungSAT-1	96
3.11	Yaw angle response of TiungSAT-1	97
4.1	Flow-chart of ANC for InnoSAT plant	108
4.2	Block Diagram of a Model Reference Adaptive System	109
4.3	Adaptive Neuro-Controller based on MRAC scheme	110
4.4	Root Locus Stability Test for Model Reference Parameter	112
4.5	Adaptive Neuro-Controller with Stabilizer	113
4.6	Root Locus Stability Test for InnoSAT plant with Lead Compensator	114
4.7	MLP network with one hidden layer	116
4.8	HMLP network with one hidden layer	117
4.9	Output Response of ANC based on HMLP network for 15 hidden nodes with one sample delay	130
4.10	Output Response of ANC based on HMLP network for 15 hidden nodes with step disturbance	131
4.11	Modified PID Controller based on MRAC scheme	133
4.12	APBB Controller based on MRAC scheme	134
4.13	Y-Thompson Spin for Roll Axis	137
4.14	Y-Thompson Spin for Pitch Axis	138
4.15	Y-Thompson Spin for Yaw Axis	138
4.16	Simulation of varying gain	140
4.17	Additive noise at the plant output	141
4.18	Step input disturbance of 5% at 300s to 600s	142
4.19	Model Reference Output for Step Input response	145

4.20	Step response of MLP, HMLP, APBB and PID controllers for InnoSAT Euler model	146
4.21	Model Reference Output for Square Wave Input	148
4.22	Performance Comparison for InnoSAT Euler model with unity gain	149
4.23	(a) is the zoom out of output response in Figure 4.22 and (b) is model following error of the zoom out response in (a)	150
4.24	Performance Comparison for InnoSAT Euler model with varying gain	151
4.25	(a) is the zoom out of output response in Figure 4.24 and (b) is model following error of the zoom out response in (a)	152
4.26	Performance Comparison for InnoSAT Euler model with measurement noise	154
4.27	(a) is the zoom out of output response in Figure 4.26 and (b) is model following error of the zoom out response in (a)	155
4.28	Performance Comparison for InnoSAT Euler model with one sample time delay	156
4.29	(a) is the zoom out of output response in Figure 4.28 and (b) is model following error of the zoom out response in (a)	157
4.30	Performance Comparison for InnoSAT Euler model with the combination all operating conditions	159
4.31	(a) is the zoom out of output response in Figure 4.30 and (b) is model following error of the zoom out response in (a)	160
4.32	Performance Comparison for InnoSAT Euler model with step disturbance	162
4.33	(a) is the zoom out of output response in Figure 4.32 and (b) is	163

	model following error of the zoom out response in (a)	
4.34	Performance Comparison for InnoSAT Euler model by using Y-Thompson spin rate data	166
4.35	(a) is the zoom out of output response in Figure 4.34 and (b) is model following error of the zoom out response in (a)	167
4.36	Step response of ANC and MPID controllers with unity gain	172
4.37	Output response of ANC and MPID controllers with unity gain	173
4.38	Output response of ANC and MPID controllers with varying gain	174
4.39	Output response of ANC and MPID controllers with measurement noise	175
4.40	Output response of ANC and MPID controllers with one sample time delay	176
4.41	Output response of ANC and MPID controllers with all operating conditions	177
4.42	(a) is output response of ANC and MPID controllers with step disturbance and (b) is the zoom out of output response in (a)	179
4.43	Output response of ANC controller using Y-Thompson spin rate data	181
4.44	The zoom out of output response in Figure 4.43	182
4.45	Block Diagram of Two Axis InnoSAT plant with Cross Coupling	183
4.46	Step Response of InnoSAT plant with cross coupling effect	185
4.47	InnoSAT response with cross coupling for unity gain	186
4.48	InnoSAT response with cross coupling for varying gain	187
4.49	InnoSAT response with cross coupling for measurement noise	188
4.50	InnoSAT response with cross coupling for step disturbance	189

4.51	InnoSAT response with cross coupling using Y-Thompson spin rate data	190
4.52	The zoom out of output response in Figure 4.51	191
5.1	Flowchart of simulator development for InnoSAT ACS system	198
5.2	Block Diagram for ACS Subsystem (middle) and other subsystems for DTUsat system	201
5.3	RCM4100 with low-EMI Rabbit 4000 based CPU	204
5.4	RCM4100 Development Kit with cable connection	205
5.5	IEEE 754 floating point segmentation standard	206
5.6	Mapping of Rabbit 4000 Physical Memory Space	210
5.7	General Block Diagram of HILS technique for InnoSAT plant	212
5.8	Satellite simulator connection for InnoSATACS system	213
5.9	Standard RS232 Cable, Programming Cable and USB Converter for RCM Development Kit	215
5.10	Match-Pattern procedure for HILS technique	216
5.11	Communication protocol between hardware simulator (HS) and software simulator (SS) for InnoSAT ACS Simulator	216
5.12	Flowchart of HILS technique for InnoSAT ACS Simulator	217
5.13	Step Response Analysis for ANC with 3 input and ANC with 8 input	221
5.14	Output Response and Model Following Error of Simulation and HILS for Euler model with step input	223
5.15	Output Response and Model Following Error of Simulation and HILS for Euler model with square wave input	225
5.16	Output Response and Model Following Error of Simulation and	227

	HILS for Euler model with varying gain	
5.17	Output Response and Model Following Error of Simulation and HILS for Euler model with measurement noise	230
5.18	Output Response and Model Following Error of Simulation and HILS for Euler model with step disturbance	232
5.19	(a) is output response of Simulation and HILS for GG model with step input and (b) is the zoom out of the output response and model following error in (a)	236
5.20	Output Response and Model Following Error of Simulation and HILS for GG model with square wave input	238
5.21	Output Response and Model Following Error of Simulation and HILS for GG model with varying gain	240
5.22	Output Response and Model Following Error of Simulation and HILS for GG model with measurement noise	242
5.23	Output Response and Model Following Error of Simulation and HILS for GG model with step disturbance	244
5.24	(a) is output response of Simulation and HILS for cross coupling with step input and (b) is the zoom out of the output response and model following error in (a)	248
5.25	Output Response and Model Following Error of Simulation and HILS for cross coupling with square wave input	251
5.26	Output Response and Model Following Error of Simulation and HILS for cross coupling with varying gain	253
5.27	Output Response and Model Following Error of Simulation and HILS for cross coupling with measurement noise	255

5.28	Output Response and Model Following Error of Simulation and HILS for cross coupling with step disturbance	257
5.29	(a) is output response of Simulation and HILS for Y-Thompson input and(b) is the zoom out of the output response in (a)	260
A.1	Definition of the orientation of the satellite axes \mathbf{u} , \mathbf{v} , \mathbf{w} in the reference frame 1, 2, 3	280
B.1	Uncompensated Root Locus for InnoSAT plant	290
B.2	Compensated Root Locus for InnoSAT plant	292
B.3	Root Locus for X axis of InnoSAT Euler Model	294
B.4	Root Locus for Lead Compensator	295
B.5	Root Locus for InnoSAT plant with Lead Compensator	296
C.1	Output Response of ANC Parameter (W1- hidden node 1)	297
C.2	Output Response of ANC Parameter (W1- hidden node 2)	298
C.3	Output Response of ANC Parameter (W1- hidden node 3)	298
C.4	Output Response of ANC Parameter (W2 - output node)	299
C.5	Output Response of ANC Parameter (WL- linear to output node)	299
C.6	Output Response of ANC Parameter (B - bias input)	300
C.7	InnoSAT response with cross coupling for 3% measurement noise	301
C.8	InnoSAT response with cross coupling for 4% measurement noise	302
C.9	InnoSAT response with cross coupling for 5% measurement noise	303

LIST OF ABBREVIATIONS

ACS	Attitude Control System
ADC	Analog to Digital converter
ADS	Attitude Determination System
ADCS	Attitude Determination and Control System
AOCS	Attitude and Orbit Control System
ANC	Adaptive Neuro-Controller
ANGKASA	National Aerospace Agency
ANN	Artificial Neural Network
APBB	Adaptive Parametric Black Box
ATSB	Astronautic Technology (M) Sdn. Bhd.
ATOF	ASCII to floating point
ARLS	Adaptive Recursive Least Square
C&DH	Command and Data Handling
CMOS	Complementary metal-oxide-semiconductor
COMM	Communication System
CFB	Circulated Fluidized-Bed
CPU	Central Processor Unit
DARPA's	Defense Advanced Research Projects Agency's
EduSAT	Educational Satellite
EDAC	Error Detection and Correction Circuit
EEPROM	Electrical Erasable Programming Read Only Memoary
EMI	Electromagnetic Interference

EPOS	European Proximity Operations Simulator
ESMO	European Student Moon Orbiter
ESA	European Space Agency
FF	Forgetting Factor
FLC	Fuzzy Logic Control
FFNN	Feed-Forward Neural Network
FBFR	Fluidized Bed Furnace Reactor
GAPSO	Genetic Algorithm Particle Swarm Optimization
GPS	Global Positioning System
GG	Gravity Gradient
GSEG	Ground Station/Segment
GIT	Georgia Institute of Technology
GPC	Generalized Predictive Control
HILS	Hardware-in-loop-simulation
HMLP	Hybrid Multi Layered Perceptron
HEO	High Earth Orbit
HS	Hardware Simulator
I ² C	Inter-integrated Circuit
IPSO	Improved Particle Swarm Optimization
InnoSAT	Innovative Satellite
LS	Least Square
LEO	Low Earth Orbit
LTI	Linear Time-Invariant
MCU	Microcontroller Unit

MEO	Medium Earth Orbit
MRP	Modified Rodrigues Parameter
MLP	Multi Layered Perceptron
MRAC	Model Reference Adaptive Control
MPID	Modified Proportional, Integral, Derivative
MPC	Model Predictive Control
MIMO	Multiple Input Multiple Output
MIT	Massachusetts Institute of Technology
MSE	Mean Square Error
MBP	Momentum Back-Propagation
NN	Neural Network
NNC	Neural Network Controller
NSO	North Sea Observer
NNSAC	Neural Network Simple Adaptive Control
NAMPC	Nonlinear Adaptive Model Predictive Control
NNMPC	Neural Network Model Predictive Control
NARMAX	Non-linear Auto-Regressive Moving Average with exogenous input
OBC	On-Board Computer
PC	Personal Computer
PSO	Particle Swarm Optimization
PD	Proportional Derivative
PID	Proportional, Integral, Derivative
P-POD	Poly-Pico Satellite Orbital Deployer
PMC	Passive Magnetic Control