

**HOMEOSTATIC-INSPIRED CONTROLLER ALGORITHM  
FOR A HYBRID-DRIVEN AUTONOMOUS UNDERWATER  
GLIDER**

**By**

**KHALID BIN ISA**

**Thesis submitted in fulfillment of the requirements  
for the degree of  
Doctor of Philosophy**

**January 2015**

## ACKNOWLEDGEMENTS

First of all, Alhamdulillah. Thank you Allah for blessing me with healthiness, strength and guidance in completing this research work and thesis. I would like to thank and express the deepest appreciation to my supervisor, Associate Professor Dr. Mohd Rizal Arshad, for having pointed me to the right direction, for his enthusiastic and wise guidance throughout my study, and for his supports, advices, brotherhood and cares, without which, this research work and thesis would not be possible. His endless enthusiasm settings and patience are something to be admired and sought after in academic, as well as life.

My deepest and utmost gratitude to my mother, Hj. Zahrah Md Jais, my lovely wife, Halijah Sa'don, and my family; they have stood by me and witnessed my study and career evolves for the better. They have also been my definite source of constant support and encouragement. To my friends at Underwater Control and Robotic Group (UCRG), USM, especially Song Yoong Siang, who have helped me with the development of the electronic system and testing, Khairul Izman Abdul Rahim, Mohd Norzaidi Mat Nawi, Herdawatie Abdul Kadir, Siti Sarah Samsuri and Shariffah Shafinar Syed Zain; thank you for your support.

Lastly, I am also indebted to Universiti Sains Malaysia (USM), Universiti Tun Hussein Onn Malaysia (UTHM) and Ministry of Education Malaysia (ERGS-203/PELECT/6730045) for funding this research, as well as allowances and living expenses. Thank you for supporting my study and this research.

## TABLE OF CONTENTS

<b>Acknowledgements</b>	ii
<b>Table of Contents</b>	iii
<b>List of Tables</b>	x
<b>List of Figures</b>	xii
<b>List of Abbreviations</b>	xix
<b>List of Symbols</b>	xxii
<b>Abstrak</b>	xxvi
<b>Abstract</b>	xxviii

### CHAPTER 1 - INTRODUCTION

1.1 Background	1
1.2 Problem Statements	4
1.3 Research Objectives	6
1.4 Research Scopes	6
1.5 Thesis Outline	9

## **CHAPTER 2 - LITERATURE REVIEW**

2.1	Introduction	12
2.2	Historical Overview of AUV and AUG	12
2.2.1	Autonomous Underwater Vehicle (AUV)	14
2.2.2	Autonomous Underwater Glider (AUG)	18
2.3	Autonomous Underwater Glider Designs and Characteristics	21
2.3.1	Mechanical Designs and Characteristics	24
2.3.2	Electronic Designs and Characteristics	26
2.3.3	Control Mechanisms	28
2.3.4	Performance Characteristics	30
2.4	Modelling of AUVs and AUGs	32
2.5	Control Methods of the AUVs and AUGs	34
2.5.1	Proportional-Integral-Derivative (PID)	34
2.5.2	Linear Quadratic Regulator (LQR)	36
2.5.3	Sliding Mode Control (SMC)	37
2.5.4	Adaptive Control	38
2.5.5	Neural Networks Control	39
2.5.6	Fuzzy Logic Control (FLC)	41
2.6	Homeostasis and the Homeostatic Control System	43
2.6.1	Overview of Homeostasis	43
2.6.2	Homeostatic Control System	44

2.6.3	The Nervous System	48
2.6.4	The Endocrine System	49
2.6.5	The Immune System	50
2.7	Summary	53

## **CHAPTER 3 - METHODOLOGY**

3.1	Introduction	55
3.2	Research Design	55
3.3	System Design	61
3.3.1	Buoyancy-Driven Mode System	64
3.3.2	Propeller-Driven Mode System	67
3.3.3	Hybrid-Driven Mode System	69
3.4	Summary	69

## **CHAPTER 4 - MODELLING OF THE HYBRID-DRIVEN UNDERWATER**

### **GLIDER**

4.1	Introduction	71
4.2	Kinematics Model	71
4.2.1	Reference Frames	72
4.2.2	Kinematics	73
4.2.3	Water Currents	75

4.2.4	Current Frame	76
4.3	Dynamics Model	78
4.3.1	Glider Configuration and Characteristics	78
4.3.2	Glider Masses Configuration	80
4.3.3	Wing and Rudder Configuration	82
4.3.4	System Inertia Matrix	83
4.3.5	Coriolis and Centripetal Forces and Moments	86
4.3.6	Damping Forces and Moments	88
4.3.7	Restoring Forces and Moments	91
4.4	Hydrodynamics Estimation	92
4.4.1	Glider Geometrical Definitions and Hydrodynamic Components	92
4.4.2	The Lift and Drag Coefficients of the Wing-Body Area from the Slender-body Theory	94
4.4.3	The Lift and Drag Coefficients of the Tail Area from the Slender-body Theory	96
4.4.4	The Lift and Drag Coefficients from CFD	97
4.5	Nonlinear Equations of Motion	97
4.6	Summary	100

## **CHAPTER 5 - THE HOMEOSTATIC CONTROLLER DESIGN AND**

### **ALGORITHM**

5.1	Introduction	101
5.2	Artificial Homeostatic Controller Design	101
5.3	Artificial Neural Network (ANN)	107
5.4	Artificial Endocrine System (AES)	111
5.5	Artificial Immune System (AIS)	114
5.6	Homeostatic Controller Algorithm	119
5.7	Summary	122

## **CHAPTER 6 - PROTOTYPE DEVELOPMENT AND SYSTEM**

### **INTEGRATION**

6.1	Introduction	123
6.2	3D Model of The Hybrid-Driven AUG	123
6.3	Mechanical Design and Fabrication	126
6.3.1	Nose, Hull and Tail	128
6.3.2	Wings and Rudder	131
6.3.3	Internal Frame	132
6.3.4	Ballast Pump	133
6.3.5	Internal Sliding Mass	134
6.4	Electronic Components and System Integration	135

6.4.1	Controller Module	136
6.4.2	Sensor Module	138
6.4.3	Internal Actuator Module	140
6.4.4	External Actuator Module	142
6.4.5	Communication Module	143
6.4.6	Data Logger Module	144
6.5	Summary	145

## **CHAPTER 7 - RESULTS AND DISCUSSION**

7.1	Introduction	146
7.2	Hydrodynamics Estimation Simulation	146
7.2.1	Hydrodynamics Analyses Based on Slender-body theory	146
7.2.2	Hydrodynamics Analyses Based on CFD	155
7.2.3	Comparison of Hydrodynamics Coefficients between Slender-body Theory and CFD	161
7.3	Homeostatic Control System Simulation	165
7.3.1	Open-loop System of the Nonlinear Model	166
7.3.2	Controllability, Observability and Stability Analysis of the Open-Loop System	168
7.3.3	Homeostatic Motion Control System Analysis	171



7.3.4	Analysis and Comparison of Homeostatic Controller	
	Performance among Different Glider Models	187
7.4	Benchmarking of Homeostatic Controller Performance	196
7.5	Prototype Testing and Experimentation	204
7.5.1	Waterproof and Buoyancy Test	204
7.5.2	Functionality and Reliability Test	206
7.5.3	Operational and Sea Trial Test	214
7.5.4	Real-Time Open-Loop System Test	216
7.5.5	Real-Time Closed-Loop System Test and Validation	222
7.6	Summary	227
<b>CHAPTER 8 - CONCLUSION AND FUTURE WORK</b>		
8.1	Conclusion	229
8.2	Future Work	231
<b>REFERENCES</b>		234
<b>APPENDICES</b>		251

## LIST OF TABLES

Table 2.1	General descriptions of the AUGs	23
Table 2.2	Mechanical designs and characteristics of the AUGs	25
Table 2.3	Electronic designs and characteristics of the AUGs	27
Table 2.4	Control mechanisms of the AUGs	29
Table 2.5	Performance characteristics of the AUGs	31
Table 2.6	The artificial homeostasis components by Neal and Timmis (2003)	45
Table 2.7	AUG designs and control methods	54
Table 4.1	Glider characteristics	79
Table 7.1	Drag force coefficient for four velocities of each area	148
Table 7.2	Drag force coefficient for four angles of attack of each area	149
Table 7.3	Lift force coefficient for four velocities of each area	150
Table 7.4	Lift force coefficient for four angles of attack of each area	151
Table 7.5	Linearisation operating point	168
Table 7.6	Controllability and observability over the system order	169
Table 7.7	Desired Euler angles for the simulation	172
Table 7.8	Translation and angular velocities for the straight gliding motion	177
Table 7.9	Predicted control inputs	180
Table 7.10	Difference percentage of gland stimulation rate between the systems with disturbance and without disturbance	182
Table 7.11	Difference percentage of hormone concentration between the systems with disturbance and without disturbance	183

Table 7.12	Comparison of the weights	187
Table 7.13	Desired Euler angles for the comparison	188
Table 7.14	Desired outputs for the comparison	196
Table 7.15	Actual pitch angle achieved by the controller	198
Table 7.16	Settling time for pitch angle	198
Table 7.17	Comparison of the translation and angular velocities	201
Table 7.18	Comparison of the position of the sliding mass in the $x$ -direction	203
Table 7.19	Comparison of the ballast masses	203
Table 7.20	Weight distribution	206
Table 7.21	Reliability test of the compass module	208
Table 7.22	IMU reliability test of the roll angle	209
Table 7.23	IMU reliability test of the pitch angle	210
Table 7.24	Reliability test of the echo sounder	211
Table 7.25	Functionality test of the servo controller and external actuators	214

## LIST OF FIGURES

Figure 1.1	Gliding motion of autonomous underwater glider (AUG)	2
Figure 2.1	The overview of the literature review	13
Figure 2.2	The basic behavioural architecture of the adaptive artificial neural-endocrine by Timmis et al. (2009)	47
Figure 2.3	Binding of hormones by Castro and Timmis (2002)	50
Figure 2.4	The adaptive immunity mechanism by Castro and Von Zuben (1999)	52
Figure 3.1	The framework diagram of methodology	56
Figure 3.2	The drawing of AUG	57
Figure 3.3	The general system architecture of the hybrid-driven AUG	62
Figure 3.4	System flowchart of the buoyancy-driven mode	66
Figure 3.5	System flowchart of the propeller-driven mode	68
Figure 3.6	System flowchart of the hybrid-driven mode	70
Figure 4.1	The glider's reference frames	72
Figure 4.2	Glider configuration	78
Figure 4.3	Geometrical definitions of the glider	93
Figure 4.4	Hydrodynamics components of the glider	94
Figure 5.1	The negative feedback of body temperature control system	102
Figure 5.2	The positive feedback of childbirth control system	103
Figure 5.3	The negative feedback of the hybrid-driven AUG motion control system	104
Figure 5.4	The artificial homeostatic control framework of the glider motion	105

Figure 5.5	The block diagram showing how to design the homeostatic controller	106
Figure 5.6	The ANN forward model of the glider plant	108
Figure 5.7	The principle of clonal selection by De Castro and Von Zuben (2000)	116
Figure 5.8	The homeostatic controller algorithm	121
Figure 6.1	The 3D model of the glider using Solidworks™	124
Figure 6.2	The evaluation of glider mass properties	126
Figure 6.3	Final prototype of the hybrid-driven autonomous underwater glider	127
Figure 6.4	Nose and echo sounder fabrication	128
Figure 6.5	The hull fabrication	129
Figure 6.6	The tail fabrication	130
Figure 6.7	The configuration of (a) wings, and (b) rudder	131
Figure 6.8	Internal frame of the hybrid-driven AUG	133
Figure 6.9	Ballast pump installation and configuration	134
Figure 6.10	Internal sliding mass installation	135
Figure 6.11	Bottom view of the internal sliding mass	135
Figure 6.12	Controller module	136
Figure 6.13	MATLAB™ code to communicate with the Arduino via serial communication	137
Figure 6.14	Arduino code to read data from MATLAB™	138
Figure 6.15	IMU and Compass	138
Figure 6.16	GPS module	140

Figure 6.17	Ballast pump control circuit	141
Figure 6.18	Linear actuator control circuit	141
Figure 6.19	Phoenix Ice2 HV40 ESC	142
Figure 6.20	The SC08A servo controller	143
Figure 6.21	The DS-XTend RF module	144
Figure 6.22	SD card data logger	145
Figure 7.1	Drag force coefficient over velocity of the glider	148
Figure 7.2	Drag force coefficient over angle of attack of the glider	149
Figure 7.3	Lift force coefficient over velocity of the glider	150
Figure 7.4	Lift force coefficient over angle of attack of the glider	151
Figure 7.5	Moment coefficient over velocity of the wing-body area	152
Figure 7.6	Moment coefficient over angle of attack of the wing-body area	152
Figure 7.7	Normal force coefficient over velocity of the glider	153
Figure 7.8	Normal force coefficient over angle of attack of the glider	153
Figure 7.9	Axial force coefficient over velocity of the glider	154
Figure 7.10	Axial force coefficient over angle of attack of the glider	154
Figure 7.11	The computational domain and grid of the hybrid-driven glider	156
Figure 7.12	Static pressure contour of the hybrid-driven glider	156
Figure 7.13	Dynamic pressure contour of the hybrid-driven glider	156
Figure 7.14	Velocity vectors of the hybrid-driven glider	157
Figure 7.15	Velocity vectors of the glider's propeller	157
Figure 7.16	Lift force coefficient over the angle of attack of the glider	158
Figure 7.17	Lift force coefficient over the velocity of the glider	158
Figure 7.18	Drag force coefficient over the angle of attack of the glider	159

Figure 7.19	Drag force coefficient over the velocity of the glider	159
Figure 7.20	Moment coefficient over the angle of attack of the glider	160
Figure 7.21	Moment coefficient over the velocity of the glider	160
Figure 7.22	Lift coefficient comparison between CFD and Slender-body theory for velocity of 0.5 m/s	161
Figure 7.23	Drag coefficient comparison between CFD and Slender-body theory for velocity of 0.5 m/s	162
Figure 7.24	Lift coefficient comparison between CFD and Slender-body theory for AoA of $2^\circ$	163
Figure 7.25	Drag coefficient comparison between CFD and Slender-body theory for AoA of $2^\circ$	163
Figure 7.26	Moment coefficient comparison between CFD and Slender-body theory for AoA of $2^\circ$	164
Figure 7.27	Moment coefficient comparison between CFD and Slender-body theory for velocity of 0.5 m/s	165
Figure 7.28	The open-loop control system of the hybrid-driven AUG	166
Figure 7.29	Simulink model for the linear model extraction	167
Figure 7.30	System poles and zeros of the hybrid-driven mode	170
Figure 7.31	System poles and zeros of the buoyancy-driven mode	171
Figure 7.32	System poles and zeros of the propeller-driven mode	171
Figure 7.33	Training performance of the neural network (NN)	173
Figure 7.34	Training regression of the neural network (NN)	173
Figure 7.35	System poles and zeros of the NN glider model for hybrid-driven mode	174
Figure 7.36	The Euler angles for the straight gliding motion	175

Figure 7.37	The translational velocities for the straight gliding motion	176
Figure 7.38	The angular velocities for the straight gliding motion	176
Figure 7.39	Position and forces of the sliding mass, and mass of the ballast pump for the straight gliding motion	178
Figure 7.40	Predicted control input for wings and rudder for the straight gliding motion	179
Figure 7.41	Predicted control input for sliding mass and ballast pump for the straight gliding motion	179
Figure 7.42	Gland stimulation rate and concentration of the AES	181
Figure 7.43	Initial antibody population	184
Figure 7.44	The best antibody	185
Figure 7.45	Cloned and matured antibody	186
Figure 7.46	Optimised antibody	186
Figure 7.47	Comparison of the pitch angle, surge and heave velocity, and pitch rate between the buoyancy-driven and hybrid-driven models	189
Figure 7.48	Comparison of the sliding mass and ballast pump outputs between the buoyancy-driven and hybrid-driven models	190
Figure 7.49	Comparison of the sliding mass and ballast control inputs between the buoyancy-driven and hybrid-driven models	192
Figure 7.50	Comparison of roll and yaw angles between the propeller-driven and hybrid-driven models	193
Figure 7.51	Comparison of the surge and sway velocities between the propeller-driven and hybrid-driven models	193



Figure 7.52	Comparison of roll and yaw rates between the propeller-driven and hybrid-driven models	194
Figure 7.53	Comparison of the wings and rudder control inputs between the propeller-driven and hybrid-driven models	195
Figure 7.54	Comparison of the controllers performance on Euler angles	197
Figure 7.55	Comparison of the controllers performance on translational velocities	200
Figure 7.56	Comparison of the controllers performance on angular velocities	200
Figure 7.57	Comparison of the controllers' performance on the sliding mass positions and forces, and the ballast mass	202
Figure 7.58	Waterproof and buoyancy test	205
Figure 7.59	Compass module reliability test	207
Figure 7.60	IMU reliability test of the roll angle	209
Figure 7.61	IMU reliability test of the pitch angle	209
Figure 7.62	Echo sounder reliability test	211
Figure 7.63	Transmitted GPS data	212
Figure 7.64	Threaded rod of the ballast pump	213
Figure 7.65	The motion of the internal sliding mass	213
Figure 7.66	Buoyancy and propeller-driven test at the Penarik Beach	215
Figure 7.67	Propeller-driven test at the sea of Bidong Island	216
Figure 7.68	Buoyancy-driven test at the sea of Bidong Island	216
Figure 7.69	Real-time open-loop system test of the hybrid-driven mode	217
Figure 7.70	Real-time open-loop system data log of the hybrid-driven mode	218

Figure 7.71	Real-time Euler angles from the open-loop system of the hybrid-driven mode	219
Figure 7.72	Real-time angular velocities from the open-loop system of the hybrid-driven mode	219
Figure 7.73	Real-time temperature, depth, and front distance from the open-loop system of the hybrid-driven mode	220
Figure 7.74	Real-time GPS data from the open-loop system of the hybrid-driven mode	221
Figure 7.75	Real-time homeostatic control system test of the hybrid-driven mode	223
Figure 7.76	Real-time homeostatic control system test data log of the hybrid-driven mode	223
Figure 7.77	Real-time Euler angles from the homeostatic control system of the hybrid-driven mode	224
Figure 7.78	Real-time angular velocities from the homeostatic control system of the hybrid-driven mode	225
Figure 7.79	Real-time temperature, depth and front distance from the homeostatic control system of the hybrid-driven mode	226
Figure 7.80	Real-time GPS data from the homeostatic control system of the hybrid-driven mode	226

## LIST OF ABBREVIATIONS

2D	-	Two-Dimensional
3D	-	Three-Dimensional
Ab	-	Antibody
ADCP	-	Acoustic Doppler Current Profiler
AES	-	Artificial Endocrine System
Ag	-	Antigen
AHRS	-	Attitude and Heading Reference System
AI	-	Artificial Intelligence
AIS	-	Artificial Immune System
ANN	-	Artificial Neural Network
AoA	-	Angle of attack
AOSN	-	Autonomous Oceanographic Sampling System
AUG	-	Autonomous Underwater Glider
AUV	-	Autonomous Underwater Vehicle
BEC	-	Battery Eliminator Circuit
BPAUV	-	Battlespace Preparation Autonomous Underwater Vehicle
CA	-	Centre of Mass
CAD	-	Computer-Aided Design
CB	-	Centre of Buoyancy
CFD	-	Computational Fluid Dynamics
CG	-	Centre of Gravity
CSA	-	Clonal Selection Algorithm
CTD	-	Conductivity, Temperature, and Depth

DC	-	Direct current
DOF	-	Degree-of-Freedom
DVL	-	Doppler Velocity Logger
ESC	-	Electronic Speed Control
FLC	-	Fuzzy Logic Control
GA	-	Genetic Algorithm
GPS	-	Global Positioning System
HDPE	-	High Density Polyethylene
HF	-	High Frequency
IDE	-	Integrated Development Environment
IMU	-	Inertial Measurement Unit
Li-Po	-	Lithium polymer
LQG	-	Linear-Quadratic-Gaussian
LQR	-	Linear-Quadratic Regulator
MIMO	-	Multiple-Input-Multiple-Output
MLP	-	Multilayer Perceptron
MMS	-	Marine Systems Simulator
MPC	-	Model Predictive Control
NACA	-	National Advisory Committee for Aeronautics
NMEA	-	National Marine Electronics Association
OMLPNN	-	Online Multilayer Perceptron Neural Network
PC	-	Personal Computer
PD	-	Proportional-Derivative
PID	-	Proportional-Integral-Derivative
PLUSNet	-	Persistent Littoral Undersea Surveillance Network

PWM	-	Pulse Width Modulation
RC	-	Radio Control
REMUS	-	Remote Environmental Monitoring Units
RF	-	Radio Frequency
ROV	-	Remotely Operated Vehicle
SCL	-	Serial clock
SD	-	Secure Digital
SDA	-	Serial data signal
SIFLC	-	Single Input Fuzzy Logic Control
SIO	-	Scripps Institution of Oceanography
SISO	-	Single-Input-Single-Output
SMC	-	Sliding Mode Control
SODMN	-	Self-Organization Direction Mapping Network
SONCS	-	Self-Organizing Neural-net Control System
SPAWAR	-	Space and Naval Warfare
SPI	-	Serial Peripheral Interface
SPURV	-	Self-Propelled Underwater Research Vehicle
UARS	-	Unmanned Arctic Research Submersible
UART	-	Universal asynchronous receiver/transmitter
USBL	-	Ultra-short Baseline
UUV	-	Unmanned Underwater Vehicle
VHF	-	Very High Frequency
WHOI	-	Woods Hole Oceanography Institute
WRC	-	Webb Research Corporation

## LIST OF SYMBOLS

$C_A(V)$	-	Added Coriolis-centripetal matrix
$\tau_A$	-	Added mass forces and moments
$M_A$	-	Added mass inertia matrix
$AC_t$	-	Aerodynamic/hydrodynamic centre of tail area
$AC_{wb}$	-	Aerodynamic/hydrodynamic centre of wing-body area
$\alpha$	-	Angle of attack
$\omega_2$	-	Angular velocities
$A_{ht}$	-	Axial force of tail area
$A_{wb}$	-	Axial force of wing-body area
$m_b$	-	Ballast point mass
$x_b y_b z_b$	-	Body reference frame axes
$B$	-	Buoyancy
$C(V)$	-	Coriolis-centripetal forces and moments
$D(V)$	-	Damping forces and moments
$\tau_{Db}$	-	Damping forces on glider body
$\tau_{Dlw}$	-	Damping forces on left wing
$\tau_{Drw}$	-	Damping forces on right wing
$\tau_{Dr}$	-	Damping forces on rudder
$\delta_{lw}$	-	Deflection angle of left wing
$\delta_{rw}$	-	Deflection angle of right wing
$\delta_r$	-	Deflection angle of rudder
$d$	-	Diameter

$C_D$	-	Drag coefficient
$m_w$	-	Fixed point mass
$\tau$	-	Forces and moments vector action on glider body
$\tau_{FK}$	-	Froude-Kriloff forces
$U$	-	Glider speed
$m_{rb}$	-	Glider total mass
$V$	-	Glider velocity
$g$	-	Gravitational acceleration
$w$	-	Heave
$m_h$	-	Hull mass
$x_{hc}$	-	Hydrodynamic centre
$I_c$	-	Inertia matrix about the centre of gravity
$I_o$	-	Inertia matrix about the origin
$x_i y_i z_i$	-	Inertial frame axes
$m_p$	-	Internal moving mass
$T$	-	Kinetic energy
$L$	-	Length of glider body
$C_L$	-	Lift coefficient
$D$	-	Linear damping
$m$	-	Mass of fluid displaced
$P_m$	-	Middle point position
$C_M$	-	Moment coefficient
$x_m$	-	Moment reference location
$m_0$	-	Net buoyancy

$D_n(V)$	-	Nonlinear damping matrix
$N_{ht}$	-	Normal force of tail area
$N_{wb}$	-	Normal force of wing-body area
$\theta$	-	Pitch angle
$q$	-	Pitch rate
$A_p$	-	Planform area
$\tau_P$	-	Propeller forces
$r$	-	Radius
$A_r$	-	Reference area
$V_r$	-	Relative velocities and accelerations to water currents
$g(n)$	-	Restoring forces and moments
$C_{RB}(V)$	-	Rigid-body Coriolis-centripetal matrix
$M_{RB}$	-	Rigid-body inertia matrix
$\phi$	-	Roll angle
$p$	-	Roll rate
$m_{py}$	-	Rotating moving mass
$J(\eta)$	-	Rotation and transformation matrix of Euler angles
$\delta$	-	Rotation angle of the wings and rudder
$R$	-	Rotation matrix
$R_{lw}$	-	Rotation matrix of left wing
$R_{rw}$	-	Rotation matrix of right wing
$R_r$	-	Rotation matrix of rudder
$\hat{\omega}_2$	-	Skew-symmetric matrix of angular velocities
$\beta$	-	Sideslip angle



## REFERENCES

- Acosta, G. G., Leon, J. F., and Mayosky, M. A. (2010). Artificial immune system inspired behavior coordination for autonomous mobile robot trajectory generation. *2010 IEEE Congress on Evolutionary Computation (CEC)*. pp. 1–6.
- Aickelin, U., and Dasgupta, D. (2005). Artificial Immune Systems. In E. Burke and G. Kendall (Eds.), *Search Methodologies SE - 13* (pp. 375–399). Springer US.
- Alam, K., Ray, T., and Anavatti, S. G. (2014). A brief taxonomy of autonomous underwater vehicle design literature. *Ocean Engineering*. 88(0): 627–630.
- Al-Enezi, J., Abbod, M., and Alsharhan, S. (2010). Artificial Immune Systems - Models, algorithms and applications. *International Journal of Research and Reviews in Applied Sciences (IJRRAS)*. 3(2): 118–131.
- Ali Hussain, N. A., Chung, T. M., Arshad, M. R., and Mohd-Mokhtar, R. (2010). Design of an underwater glider platform for shallow-water applications. *International Journal of Intelligent Defence Support Systems*. 3(3): 186–206.
- Allen, B., Stokey, R., Austin, T., Forrester, N., Goldsborough, R., Purcell, M., and von Alt, C. (1997). REMUS: a small, low cost AUV; system description, field trials and performance results. *OCEANS '97. MTS/IEEE Conference Proceedings*. pp. 994-1000.
- Alvarez, A., Caffaz, A., Caiti, A., Casalino, G., Clerici, E., Giorgi, F., Gualdesi, L., et al. (2004). Design and realization of a very low cost prototypal autonomous vehicle for coastal oceanographic missions. *Proc. IFAC Conf. Control Applications in Marine Systems, CAMS'04, Ancona, Italy*. pp. 471–476.
- Alvarez, A., Caffaz, A., Caiti, A., Casalino, G., Gualdesi, L., Turetta, A., and Viviani, R. (2009). Folaga: A low-cost autonomous underwater vehicle combining glider and AUV capabilities. *Ocean Engineering*. 36(1): 24–38.
- Amin, R., Khayyat, A. A., and Osgouie, K. G. (2010a). Neural networks modeling of autonomous underwater vehicle. *2010 IEEE/ASME International Conference on Mechatronics and Embedded Systems and Applications (MESA)*. pp. 14–19.
- Amin, R., Khayyat, A. A., and Osgouie, K. G. (2010b). Neural networks control of autonomous underwater vehicle. *2010 2nd International Conference on Mechanical and Electronics Engineering (ICMEE)*. vol. 2. pp. 117–121.
- Amjad, M., Ishaque, K., Abdullah, S. S., and Salam, Z. (2010). An alternative approach to design a Fuzzy Logic Controller for an autonomous underwater vehicle. *2010 IEEE Conference on Cybernetics and Intelligent Systems (CIS)*. pp. 195–200.

- Antonelli, G. (2007). On the Use of Adaptive/Integral Actions for Six-Degrees-of-Freedom Control of Autonomous Underwater Vehicles. *IEEE Journal of Oceanic Engineering*. 32(2): 300–312.
- Antonelli, G, Chiaverini, S., Sarkar, N., and West, M. (2001). Adaptive control of an autonomous underwater vehicle: experimental results on ODIN. *IEEE Transactions on Control Systems Technology*. 9(5): 756–765.
- Antonelli, Gianluca, Fossen, T., and Yoerger, D. (2008). Underwater Robotics. In B. Siciliano and O. Khatib (Eds.), *Springer Handbook of Robotics SE - 44* (pp. 987–1008). Springer Berlin Heidelberg.
- Arima, M., Ichihashi, N., and Ikebuchi, T. (2008). Motion characteristics of an underwater glider with independently controllable main wings. *Oceans 2008 - MTS/IEEE Kobe Techno-Ocean*. pp. 951–957.
- Arima, M., Ichihashi, N., and Miwa, Y. (2009). Modelling and Motion Simulation of an Underwater Glider with Independently Controllable Main Wings. *Oceans 2009 - Europe*. pp. 472–477.
- Asakawa, K, Nakamura, M., Kobayashi, T., Watanabe, Y., Hyakudome, T., Ito, Y., and Kojima, J. (2011). Design concept of Tsukuyomi-Underwater glider prototype for virtual mooring. *OCEANS, 2011 IEEE - Spain*. pp. 1-5.
- Asakawa, Kenichi, Kobayashi, T., Nakamura, M., Watanabe, Y., Hyakudome, T., Itoh, Y., and Kojima, J. (2012). Results of the First Sea-test of Tsukuyomi. In *Ocean 2012*. pp. 4–8.
- Astrov, I., and Pedai, A. (2011). Multirate depth control of an AUV by neural network predictive controller for enhanced situational awareness. *2011 5th International Symposium on Computational Intelligence and Intelligent Informatics (ISCIII)*. pp. 47–52.
- Avila-Garcia, O., and Cañamero, L. (2004). Using hormonal feedback to modulate action selection in a competitive scenario. *From Animals to Animats 8*. pp. 243–252.
- Bachmayer, R., Graver, J. G., and Leonard, N. E. (2003). Glider control: a close look into the current glider controller structure and future developments. *Proceedings of OCEANS 2003*. vol. 2. pp. 951–954.
- Bao, L., Junhong, W., and Huachao, Q. (2011). A novel neural network inspired from Neuroendocrine-Immune System. *The 2011 International Joint Conference on Neural Networks (IJCNN)*. pp. 2382-2386.
- Baoquan, L., and Keqiang, H. (1997). The nonlinear control using fuzzy logic for spinning underwater vehicle. *ICIPS '97. 1997 IEEE International Conference on Intelligent Processing Systems, 1997*. vol. 1. pp. 223–226.

- Barros, E. A., Dantas, J. L., Pascoal, A. M., & de Sa, E. (2008). Investigation of normal force and moment coefficients for an AUV at nonlinear angle of attack and sideslip range. *IEEE Journal of Oceanic Engineering*. 33(4): 538-549.
- Bender, A., Steinberg, D. M., Friedman, A. L., and Williams, S. B. (2008). Analysis of an Autonomous Underwater Glider. *In Australasian Conference on Robotics and Automation*. pp. 1–10.
- Besedovsky, H. O., and Rey, A. Del. (1996). Immune-neuro-endocrine interactions: facts and hypotheses. *Endocrine reviews*. 17(1): 64–102.
- Bhatta, P., and Leonard, N. E. (2002). Stabilization and coordination of underwater gliders. *Proceedings of the 41st IEEE Conference on Decision and Control*. vols. 1-4. pp. 2081–2086.
- Blidberg, D. R. (2001). The development of autonomous underwater vehicles (auvs); a brief summary. *IEEE ICRA*. vol. 4.
- Bradley, D., and Tyrrell, A. (2002). A hardware immune system for benchmark state machine error detection. *CEC '02. Proceedings of the 2002 Congress on Evolutionary Computation, 2002*. vol. 1. pp. 813–818.
- Budiyo, A. (2009). Advances in unmanned underwater vehicles technologies : Modeling , control and guidance perspectives. *Indian Journal of Geo-Marine Sciences*. 38(3): 282–295.
- Budiyo, A. (2011). Model predictive control for autonomous underwater vehicle. *Indian Journal of Geo-Marine Sciences*. 40(2): 191–199.
- Caffaz, A., Caiti, A., Casalino, G., and Turetta, A. (2010). The Hybrid Glider/AUV Folaga. *Robotics & Automation Magazine, IEEE*. 17(1): 31-44.
- Caiti, A., and Calabro, V. (2010). Control-oriented modelling of a hybrid AUV. *2010 IEEE International Conference on Robotics and Automation (ICRA)*. pp. 5275–5280.
- Campa, G., Innocenti, M., and Nasuti, F. (1998). Robust control of underwater vehicles: sliding mode control vs. mu synthesis. *OCEANS '98 Conference Proceedings*. vol. 3. pp. 1640–1644.
- Canon, W. B. (1932). *The Wisdom of Body* (Rev. and E., p. 281). New York: Norton.
- Castro, L. N., and Von Zuben, F. J. (2000). The clonal selection algorithm with engineering applications. *Proceedings of GECCO*. pp. 36–42.
- Castro, L. N., and Timmis, J. (2002). *Artificial Immune Systems: A New Computational Intelligence Approach*. (pp. 380). Springer.

- Castro, L. N., and Von Zuben, F. J. (1999). *Technical Report, Artificial Immune Systems: Part I – Basic Theory and Applications*. pp. 1–87.
- Chellabi, A., and Nahon, M. (1993). Feedback linearization control of undersea vehicles. *OCEANS '93. Engineering in Harmony with Ocean. Proceedings*. vol. 1. pp. I410–I415.
- Chingtham, T. S., Sahoo, G., and Ghose, M. K. (2010). An Artificial Immune System Model for Multi Agents Resource Sharing in Distributed Environments. (*IJCSE*) *International Journal on Computer Science and Engineering*. 02(05): 1813–1818.
- Chiu, F. C., Guo, M. F., Guo, J., and Lee, S. K. (2008). Modular Modeling of Maneuvering Motions of an Underwater Glider. *Oceans 2008*. vols. 1-4. pp. 503–510.
- Choi, S. K., Takashige, G. Y., and Yuh, J. (1994). Experimental study on an underwater robotic vehicle: ODIN. *Proceedings of the 1994 Symposium on Autonomous Underwater Vehicle Technology, 1994. AUV '94*. pp. 79–84.
- Christ, R. D., and Wernli Sr, R. L. (2007). *The ROV Manual A User Guide for Observation-Class Remotely Operated Vehicles* (pp. 320). Butterworth-Heinemann, Elsevier Ltd.
- Cohen, I. R. (2007). Real and artificial immune systems: computing the state of the body. *Nature Reviews Immunology*. 7(7): 569–574. Nature Publishing Group.
- Cristi, R., and Healey, A. J. (1989). Adaptive Identification and Control of an Autonomous Underwater Vehicle. *Proceedings of the 6th International Symposium on Unmanned Untethered Submersible Technology*. pp. 563–572.
- Curtin, T., Bellingham, J., Catipovic, J., and Webb, D. (1993). Autonomous Oceanographic Sampling Networks. *Oceanography*. 6(3): 86–94.
- Damus, R., Manley, J., Desset, S., Morash, J., and Chryssostomidis, C. (2002). Design of an Inspection Class Autonomous Underwater Vehicle. *OCEANS '02 MTS/IEEE*. pp. 180–185.
- Dasgupta, D, Ji, Z., and Gonzalez, F. (2003). Artificial immune system (AIS) research in the last five years. *The 2003 Congress on Evolutionary Computation, CEC '03*. vol. 1. pp. 123–130.
- Dasgupta, D. (1999). An Overview of Artificial Immune Systems and Their Applications. In Dipankar Dasgupta (Ed.), *Artificial Immune Systems and Their Applications SE - 1* (pp. 3–21). Springer Berlin Heidelberg.
- Davis, R. E., Webb, D. C., Regier, L. A., and Dufour, J. (1992). The Autonomous Lagrangian Circulation Explorer (ALACE). *Journal of Atmospheric and Oceanic Technology*. 9: 264–285.

- DeBitetto, P. A. (1995). Fuzzy logic for depth control of Unmanned Undersea Vehicles. *IEEE Journal of Oceanic Engineering*. 20(3): 242–248.
- Dong, E., Guo, S., Lin, X., Li, X., and Wang, Y. (2012). A neural network-based self-tuning PID controller of an autonomous underwater vehicle. *2012 International Conference on Mechatronics and Automation (ICMA)*. pp. 898–903.
- Dougherty, F., Sherman, T., Woolweaver, G., and Lovell, G. (1988). An autonomous underwater vehicle (AUV) flight control system using sliding mode control. *OCEANS '88. A Partnership of Marine Interests. Proceedings*. vol. 4. pp. 1265–1270.
- Dyke, J. G., and Harvey, I. R. (2006). Pushing up the daisies. *10th International Conference on the Simulation and Synthesis of Living Systems*. pp. 426–431.
- Dyke, J., and Harvey, I. (2005). Hysteresis and the limits of homeostasis: from daisyworld to phototaxis. *Proceedings of the 8th European conference on Advances in Artificial Life*. pp. 241–251.
- Eriksen, C. C, Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., and Ballard, J. W. (2001). Seaglider: a long-range autonomous underwater vehicle for oceanographic research. *IEEE Journal of Oceanic Engineering*. 26(4): 424–436.
- Eriksen, C. C. (2003). Autonomous Underwater Gliders. *Technical Report, Autonomous and Lagrangian Platforms and Sensors (ALPS) Workshop* (pp. 1–5). Sea Lodge, La Jolla CA.
- Etkin, B., and Reid, L. D. (1995). *Dynamics of Flight: Stability and Control* (3rd Editio., (pp. 400). Wiley.
- Evans, J. C., Keller, K. M., Smith, J. S., Marty, P., and Rigaudo, O. V. (2001). Docking techniques and evaluation trials of the SWIMMER AUV: an autonomous deployment AUV for work-class ROVs. *OCEANS, 2001. MTS/IEEE Conference and Exhibition*. pp. 520-528.
- Evans, J., Redmond, P., Plakas, C., Hamilton, K., and Lane, D. (2003). Autonomous docking for Intervention-AUVs using sonar and video-based real-time 3D pose estimation. *OCEANS 2003. Proceedings*. vol. 4. pp. 2201-2210.
- Ezequiel A. Di Paolo. (2000). Homeostatic Adaptation to Inversion of the Visual Field and Other Sensorimotor Disruptions. *From Animals to Animals: Proceedings of the 6th International Conference on the Simulation of Adaptive Behavior*. pp. 440–449.
- Fan, S. and Woolsey, C. (2014). Dynamics of Underwater Gliders in Currents. *Ocean Engineering*. In Press, Corrected Proof, Available online 16 April 2014.



- Fjellstad, O.-E., and Fossen, T. I. (1994). Position and attitude tracking of AUV's: a quaternion feedback approach. *IEEE Journal of Oceanic Engineering*. 19(4): 512–518.
- Forrest, S., Hofmeyr, S. A., and Somayaji, A. (1997). Computer immunology. *Communications of the ACM*. 40(10): 88–96.
- Forrest, S., Perelson, A. S., Allen, L., and Cherukuri, R. (1994). Self-nonsel discrimination in a computer. *1994 IEEE Computer Society Symposium on Research in Security and Privacy, 1994. Proceedings*. pp. 202–212.
- Fossen, T. I. (1994). *Guidance and control of ocean vehicles*. New York. John Wiley and Sons.
- Fossen, T. I. (2002). *Marine control systems: Guidance, navigation and control of ships, rigs and underwater vehicles*. Marine Cybernetics Trondheim.
- Fossen, T. I. (2011). *Handbook of marine craft hydrodynamics and motion control*. John Wiley & Sons.
- Fujii, T. (1995). Neural networks for ocean engineering. *IEEE International Conference on Neural Networks, 1995. Proceedings*, vol. 1. pp. 216–219.
- García-Córdova, F., and Guerrero-González, A. (2011). A Biologically Inspired Neural Network for Autonomous Underwater Vehicles. In J. Cabestany, I. Rojas, & G. Joya (Eds.), *Advances in Computational Intelligence SE - 21* (vol. 6691, pp. 166–173). Springer Berlin Heidelberg.
- Geisbert, J. S. (2007). *Hydrodynamic Modeling for Autonomous Underwater Vehicles using Computational and Semi-empirical Methods*. Thesis. Virginia Polytechnic Institute and State University, Virginia.
- Gertler, M., and Hagen, G. R. (1967). *Standard equations of motion for submarine simulation*. DTIC Document.
- Goheen, K. R., and Jefferys, E. R. (1990). Multivariable self-tuning autopilots for autonomous and remotely operated underwater vehicles. *IEEE Journal of Oceanic Engineering*. 15(3): 144–151.
- Graver, J. G., and Leonard, N. E. (2001). Underwater glider dynamics and control. *12th international symposium on unmanned untethered submersible technology*. pp. 1742–1710.
- Graver, J. G. (2005). *Underwater Gliders: Dynamics, Control and Design*. Thesis. Princeton University.
- Griffiths, G., Davis, R. E., Eriksen, C. C., and Jones, C. P. (2002). Autonomous buoyancy-driven underwater gliders. In G Griffiths (Ed.), (In: Techno.). London: Taylor and Francis.

- Griffiths, Gwynn, Jones, C., Ferguson, J., and Bose, N. (2007). Undersea gliders. *Journal of Ocean Technology*. 2(2): 64–75.
- Guo, J., Chiu, F. C., and Chieh-Chih, W. (1995). Adaptive control of an autonomous underwater vehicle testbed using neural networks. *OCEANS '95. MTS/IEEE. Challenges of Our Changing Global Environment. Conference Proceedings*. vol. 2. pp. 1033–1039.
- Guo, J., and Huang, S. H. (1996). Control of an autonomous underwater vehicle testbed using fuzzy logic and genetic algorithms. *Proceedings of the 1996 Symposium on Autonomous Underwater Vehicle Technology, AUV '96*. pp. 485–489.
- Hagan, M. T., Demuth, H. B., and Jesús, O. D. (2002). An introduction to the use of neural networks in control systems. *International Journal of Robust and Nonlinear Control*. 12(11): 959–985.
- Haktanirlar Ulutas, B., and Kulturel-Konak, S. (2011). A review of clonal selection algorithm and its applications. *Artificial Intelligence Review*. 36(2): 117–138.
- Harvey, I. (2004). Homeostasis and rein control: From daisyworld to active perception. *Proceedings of the Ninth International Conference on the Simulation and Synthesis of Living Systems, ALIFE*. pp. 309–314.
- Healey, A. J., and Lienard, D. (1993). Multivariable sliding mode control for autonomous diving and steering of unmanned underwater vehicles. *IEEE Journal of Oceanic Engineering*. 18(3): 327–339.
- Hills, S. J., and Yoerger, D. R. (1994). A nonlinear sliding mode autopilot for unmanned undersea vehicles. *OCEANS '94. 'Oceans Engineering for Today's Technology and Tomorrow's Preservation.'* *Proceedings*. vol. 3. pp. 93–98.
- Hobson, B., Schulz, B., Janet, J., Kemp, M., Moody, R., Pell, C., and Pinnix, H. (2001). Development of a micro autonomous underwater vehicle for complex 3-D sensing. *OCEANS, 2001. MTS/IEEE Conference and Exhibition*. vol. 4. pp. 2043–2045.
- Hoerner, S. F., and Borst, H. V. (1985). *Fluid-Dynamic Lift*. (H. V. Borst, Ed.) (Second Edi.). Hoerner Fluid Dynamics.
- Hoerner, and Sighard, F. (1975). *Fluid-Dynamic Lift*. Brick Town, NJ: Hoerner Fluid Dynamics.
- Hoinville, T., and Henaff, P. (2004). Comparative study of two homeostatic mechanisms in evolved neural controllers for legged locomotion. *Proceedings. 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2004. (IROS 2004)*. vol. 3. pp. 2624–2629.

- Hussain, N. A. A., Arshad, M. R., and Mohd-Mokhtar, R. (2011). Underwater glider modelling and analysis for net buoyancy, depth and pitch angle control. *Ocean Engineering*. 38(16): 1782–1791.
- Ichihashi, N., Ikebuchi, T., and Arima, M. (2008). Development of an Underwater Glider with Independently Controllable Main Wings. In J. S. Chung, S. T. Grilli, S. Naito, & Q. Ma (Eds.), *Proceedings of the Eighteenth International Offshore and Polar Engineering Conference*. pp. 156–161.
- Innocenti, M., and Campa, G. (1999). Robust control of underwater vehicles: sliding mode vs. LMI synthesis. *Proceedings of the 1999 American Control Conference*. vol. 5. pp. 3422–3426.
- Ishaque, K., Abdullah, S. S., Ayob, S. M., and Salam, Z. (2010). Single Input Fuzzy Logic Controller for Unmanned Underwater Vehicle. *Journal of Intelligent and Robotic Systems*. 59(1): 87–100.
- Ishii, K, Fujii, T., and Ura, T. (1994). A quick adaptation method in a neural network based control system for AUVs. *Proceedings of the 1994 Symposium on Autonomous Underwater Vehicle Technology, AUV '94*. pp. 269–274.
- Ishii, K, Fujii, T., and Ura, T. (1995). An on-line adaptation method in a neural network based control system for AUVs. *IEEE Journal of Oceanic Engineering*. 20(3): 221–228.
- Ishii, K, Ura, T., and Fujii, T. (1994). A feedforward neural network for identification and adaptive control of autonomous underwater vehicles. *IEEE World Congress on Computational Intelligence., 1994 IEEE International Conference on Neural Networks*. vol. 5. pp. 3216–3221.
- Ishii, Kazuo, and Ura, T. (2000). An adaptive neural-net controller system for an underwater vehicle. *Control Engineering Practice*. 8(2): 177–184.
- Jagadeesh, P., Murali, K., and Idichandy, V. G. (2009). Experimental investigation of hydrodynamic force coefficients over AUV hull form. *Ocean Engineering*. 36(1): 113–118.
- Jalving, B. (1994). The NDRE-AUV flight control system. *IEEE Journal of Oceanic Engineering*. 19(4): 497–501.
- Jenkins, S. A., Humphreys, D. E., Sherman, J., Osse, J., Jones, C., Leonard, N., Graver, J., et al. (2003). *Technical Report, Underwater Glider System Study*.
- Jerne, N. K. (1973). The Immune System. *Scientific American*. 229(1): 52–60.
- Ji Hong, L., Pan Mook, L., and Bong Huan, J. (2004). Application of a robust adaptive controller to autonomous diving control of an AUV. *30th Annual Conference of IEEE Industrial Electronics Society, IECON 2004*. vol. 1. pp. 419–424.



- Ji-Hong, L., Pan-Mook, L., and Sang Jeong, L. (2002). Neural net based nonlinear adaptive control for autonomous underwater vehicles. *Proceedings of IEEE International Conference on Robotics and Automation ICRA '02*. vol. 2. pp. 1075–1080.
- Jorgensen, L. H. (1973). *A method for estimating static aerodynamic characteristics for slender bodies of circular and noncircular cross section alone and with lifting surfaces at angles of attack from  $0^\circ$  to  $90^\circ$*  (pp. 1–17).
- Jun, B.-H., Park, J.-Y., Lee, F.-Y., Lee, P.-M., Lee, C.-M., Kim, K., and Lim, Y.-K. (2009). Development of the AUV “ISiMI” and a free running test in an Ocean Engineering Basin. *Ocean Engineering*. 36(1): 2–14.
- Kan, L., Zhang, Y., Fan, H., Yang, W., and Chen, Z. (2008). MATLAB-based simulation of buoyancy-driven underwater glider motion. *Journal of Ocean University of China*. 7(1): 113–118.
- Kawaguchi, K., Ura, T., Tomoda, Y., and Kobayashi, H. (1993). Development and Sea Trials of a Shuttle Type AUV “ALBAC”. *Eighth International Symposium on Unmanned Untethered Submersible Technology*. pp. 7–13.
- Koh, T. H., Lau, M. W. S., Low, E., Seet, G., Swei, S., and Cheng, P. L. (2002). A study of the control of an underactuated underwater robotic vehicle. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. vol. 2. pp. 2049–2054.
- Lee, P.-M., Hong, S.-W., Lim, Y.-K., Lee, C.-M., Jeon, B.-H., and Park, J.-W. (1999). Discrete-time quasi-sliding mode control of an autonomous underwater vehicle. *IEEE Journal of Oceanic Engineering*. 24(3): 388–395.
- Lee, W., and Kang, G. (1998). A fuzzy model-based controller of an underwater robotic vehicle under the influence of thruster dynamics. *1998 IEEE International Conference on Robotics and Automation. Proceedings*. vol. 1. pp. 750–755.
- Leonard, N. E., and Graver, J. G. (2001). Model-based feedback control of autonomous underwater gliders. *IEEE Journal of Oceanic Engineering*. 26(4): 633–645.
- Li, J. H., and Lee, P. M. (2005). A neural network adaptive controller design for free-pitch-angle diving behavior of an autonomous underwater vehicle. *Robotics and Autonomous Systems*. 52(2–3): 132–147.
- Li, Y., Jian-Cheng, L., and Ming-Xue, S. (2005). Dynamics Model of Underwater Robot Motion Control in 6 Degrees of Freedom. *Journal of Harbin Institute of Technology*. 12(4): 456 – 459.

- Mahesh, H., Yuh, J., and Lakshmi, R. (1991). Control of underwater robots in working mode. *Proceedings of 1991 IEEE International Conference on Robotics and Automation*. vol. 3. pp. 2630–2635.
- Mahmoudian, N., Geisbert, J., and Woolsey, C. (2010). Approximate Analytical Turning Conditions for Underwater Gliders: Implications for Motion Control and Path Planning. *IEEE Journal of Oceanic Engineering*. 35(1): 131–143.
- Mahmoudian, N., and Woolsey, C. (2008). Underwater glider motion control. *47th IEEE Conference on Decision and Control, CDC 2008*. pp. 552–557.
- Mahmoudian, N. (2009). *Efficient Motion Planning and Control for Underwater Gliders*. Thesis. Virginia Polytechnic Institute and State University.
- Marco, D. B., and Healey, A. J. (2001). Command, control, and navigation experimental results with the NPS ARIES AUV. *IEEE Journal of Oceanic Engineering*. 26(4): 466–476.
- Marco, D. B., Healey, A. J., McGhee, R. B., Brutzman, D. P., and Cristi, R. (2005). *Control Systems Architecture, Navigation, and Communication Research Using the NPS Phoenix Underwater Vehicle*. DTIC Document.
- Marthiniussen, R., Vestgard, K., Klepaker, R. A., and Storkersen, N. (2004). HUGIN-AUV concept and operational experiences to date. *OCEANS '04. MTS/IEEE TECHNO-OCEAN '04*. vol. 2. pp. 846–850.
- Matzinger, P. (2002). The danger model: a renewed sense of self. *Science*, 296(5566), 301–305. American Association for the Advancement of Science.
- McClintic, J. R. (1975). *Basic Anatomy and Physiology of the Human Body* (pp. 658). John Wiley & Sons Inc.
- McGann, C., Py, F., Rajan, K., Ryan, J. P., and Henthorn, R. (2008). Adaptive Control for Autonomous Underwater Vehicles. *23rd AAAI Conference of Artificial Intelligence*. pp. 1319–1324.
- Meshref, H., and VanLandingham, H. (2000). Artificial immune systems: application to autonomous agents. *2000 IEEE International Conference on Systems, Man, and Cybernetics*. vol. 1. pp. 61–66.
- Meshref, H., and VanLandingham, H. (2001). Immune network simulation of reactive control of a robot arm manipulator. *Proceedings of the 2001 IEEE Mountain Workshop on Soft Computing in Industrial Applications, SMCia/01*. pp. 81–85.

- Moioli, R. C., Vargas, P. A., and Husbands, P. (2009). A Multiple Hormone Approach to the Homeostatic Control of Conflicting Behaviours in an Autonomous Mobile Robot. *2009 IEEE Congress on Evolutionary Computation*. vols. 1-5. pp. 47–54.
- Moioli, R. C., Vargas, P. A., Von Zuben, F. J., and Husbands, P. (2008a). Evolving an Artificial Homeostatic System. In G. Zaverucha & A. LoureiroDaCosta (Eds.), *Advances in Artificial Intelligence - Sbia 2008, Proceedings*. vol. 5249. pp. 278–288.
- Moioli, R. C., Vargas, P. A., Von Zuben, F. J., and Husbands, P. (2008b). Towards the evolution of an artificial homeostatic system. *IEEE Congress on Evolutionary Computation and IEEE World Congress on Computational Intelligence*. pp. 4023–4030.
- Moitie, R., and Seube, N. (2001). Guidance and control of an autonomous underwater glider. *Proc. 12th Int. Symposium on Unmanned Untethered Submersible Tech.* pp. 14.
- Narasimhan, M., and Singh, S. N. (2006). Adaptive input–output feedback linearizing yaw plane control of BAUV using dorsal fins. *Ocean Engineering*. 33(11–12): 1413–1430.
- Neal, M., and Timmis, J. (2003). Timidity: A Useful Mechanism for Robot Control? *Informatica*. 27(4): 197–204.
- Neal, M., and Timmis, J. (2005). Recent Developments in Biologically Inspired Computing. *Idea Group Publishing, chapter: Once More unto the Breach: Towards Artificial Homeostasis*. pp. 340–365.
- Nie, J., Yuh, J., Kardash, E., and Fossen, T. I. (2000). On-board sensor-based adaptive control of small UUVs in very shallow water\*. *International Journal of Adaptive Control and Signal Processing*. 14(4): 441–452.
- Nishida, S, Ishii, K., and Furukawa, T. (2006). An Adaptive Neural Network Control System using mnSOM. *OCEANS 2006 - Asia Pacific*. pp. 1–6.
- Nishida, Shuhei, Ishii, K., and Furukawa, T. (2006). An adaptive controller system using mnSOM. *International Congress Series*. 1291(0): 181–184.
- Noh, M. M., Arshad, M. R., and Mokhtar, R. M. (2011). Depth and pitch control of USM underwater glider: performance comparison PID vs. LQR. *Indian Journal of Geo-Marine Sciences*. 40(2), 200–206.
- Olden, J. D., and Jackson, D. A. (2002). Illuminating the “black box”: a randomization approach for understanding variable contributions in artificial neural networks. *Ecological modelling*. 154(1). 135-150.

- ONR. (2006). Liberdade XRAY Advanced Underwater Glider. *ONR press release*. Retrieved August 30, 2013, from [http://auvac.org/uploads/platform\\_pdf/Liberdade\\_advanced\\_underwater\\_glider.pdf](http://auvac.org/uploads/platform_pdf/Liberdade_advanced_underwater_glider.pdf)
- Osse, T. J., and Eriksen, C. C. (2007). The Deepglider: A Full Ocean Depth Glider for Oceanographic Research. *OCEANS 2007*. pp. 1–12.
- Osse, T. J., and Lee, T. J. (2007). Composite Pressure Hulls for Autonomous Underwater Vehicles. *OCEANS 2007*. pp. 1-14.
- Owens, N., Timmis, J., Greensted, A., and Tyrell, A. (2007). On Immune Inspired Homeostasis for Electronic Systems. In L. Castro, F. Zuben, and H. Knidel (Eds.), *Artificial Immune Systems SE - 19* (vol. 4628, pp. 216–227). Springer Berlin Heidelberg.
- Patterson, M. R., and Sias, J. H. (1999). Modular Autonomous Underwater Vehicle System. Patent. United States.
- Peng, S., Yang, C., Fan, S., Zhang, S., Wang, P., Xie, Y., and Chen, Y. (2013). A hybrid underwater glider for underwater docking. *Oceans - San Diego*. pp. 1–7.
- Raza, A., and Fernandez, B. R. (2010). Immuno-inspired heterogeneous mobile robotic systems. *2010 49th IEEE Conference on Decision and Control (CDC)*. pp. 7178–7183.
- Rish III, J. W., Willcox, S., Grieve, R., Montieth, I., and Vaganay, J. (2001). Operational testing of the Battlespace Preparation AUV in the shallow water regime. *OCEANS, 2001. MTS/IEEE Conference and Exhibition*. pp. 123-129.
- Roberts, G. N., and Sutton, R. (2006). Advances in unmanned marine vehicles. IEE Control Series (pp. 464). Institution of Electrical Engineers.
- Rodrigues, L., Tavares, P., and Prado, M. (1996). Sliding mode control of an AUV in the diving and steering planes. *OCEANS '96. MTS/IEEE. Prospects for the 21st Century. Conference Proceedings*. vol. 2. pp. 576–583.
- Rodríguez, P., and Piera, J. (2005). Mini AUV, a platform for future use on marine research for the Spanish Research Council? *Instrumentation ViewPoint. Autumn 2005*. pp. 14–15.
- Rudnick, D. L., Davis, R. E., Eriksen, C. C., Fratantoni, D. M., and Perry, M. J. (2004). Underwater gliders for ocean research. *Marine Technology Society Journal*. 38(2): 73–84.
- Sagala, F., and Bambang, R. T. (2011). Development of sea glider autonomous underwater vehicle platform for marine exploration and monitoring. *Indian Journal of Marine Sciences*. 40(2): 287–295.

- Santora, M., Alberts, J., and Edwards, D. (2006). Control of Underwater Autonomous Vehicles Using Neural Networks. *OCEANS 2006*. pp. 1–5.
- Sarath Babu, S., Kumar, C. S., and Faruqi, M. A. (2006). A Neural Network Online Controller for Autonomous Underwater Vehicle. *IEEE International Conference on Industrial Technology, ICIT 2006*. pp. 2320–2324.
- Schmickl, T., Hamann, H., and Crailsheim, K. (2011). Modelling a hormone-inspired controller for individual-and multi-modular robotic systems. *Mathematical and Computer Modelling of Dynamical Systems*. 17(3): 221–242.
- Seo, D. C., Jo, G., and Choi, H. S. (2008). Pitching control simulations of an underwater glider using CFD analysis. *Oceans 2008 - MTS/IEEE Kobe Techno-Ocea.*, vols. 1-3. pp. 476–480.
- Shen, W., Will, P., and Galstyan, A. (2004). Hormone-Inspired Self-Organization and Distributed Control of Robotic Swarms. *Autonomous Robots*. 17(1): 93–105.
- Sherman, J., Davis, R. E., Owens, W. B., and Valdes, J. (2001). The autonomous underwater glider “spray.” *IEEE Journal of Oceanic Engineering*. 26(4): 437–446.
- Shridhar, R., and Cooper, D. J. (1997). A Tuning Strategy for Unconstrained SISO Model Predictive Control. *Ind. Eng. Chem. Res.* 36(3): 729–746.
- Sibenac, M., Kirkwood, W. J., McEwen, R., Shane, F., Henthorn, R., Gashler, D., and Thomas, H. (2002). Modular AUV for routine deep water science operations. *OCEANS '02 MTS/IEEE*. pp. 167–172.
- Simonetti, P. (1992). *Slocum Glider, Design and 1991 Field Trials*. Webb Resesearch Corporation Internal Report.
- Sliwka, J., Clement, B., and Probst, I. (2012). Sea glider guidance around a circle using distance measurements to a drifting acoustic source. *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. pp. 94–99.
- Smallwood, D. A., and Whitcomb, L. L. (2004). Model-based dynamic positioning of underwater robotic vehicles: theory and experiment. *IEEE Journal of Oceanic Engineering*. 29(1): 169–186.
- Smith, S. M., Rae, G. J. S., Anderson, D. T., and Shein, A. M. (1994). Fuzzy logic control of an autonomous underwater vehicle. *Control Engineering Practice*. 2(2): 321–331.
- Soloway, D., and Haley, P. J. (1996). Neural generalized predictive control. *Proceedings of the 1996 IEEE International Symposium on Intelligent Control*. pp. 277–282.



- Song, F., An, P. E., and Folleco, A. (2003). Modeling and simulation of autonomous underwater vehicles: design and implementation. *IEEE Journal of Oceanic Engineering*. 28(2): 283–296.
- Sørensen, A. J. (2005). Marine cybernetics: Modelling and control. *Lecture Notes, Fifth Edition, UK-05-76, Department of Marine Technology, the Norwegian University of Science and Technology, Trondheim, Norway*.
- Stevens, B. L., and Lewis, F. L. (1992). *Aircraft Control and Simulation*. New York, NY: Wiley.
- Stevenson, P. (1996). Development of reliable sub systems for Autosub. *OCEANS '96. MTS/IEEE. Prospects for the 21st Century. Conference Proceedings*. vol. 2. pp. 711-716.
- Stokey, R. P., Roup, A., von Alt, C., Allen, B., Forrester, N., Austin, T., and Goldsborough, R. (2005). Development of the REMUS 600 Autonomous Underwater Vehicle. *Proceedings of OCEANS 2005 MTS/IEEE*. pp. 1–4.
- Stommel, H. (1989). The Slocum mission. *Oceanography*. 2: 22–25.
- Tang, S., Ura, T., Nakatani, T., Thornton, B., and Jiang, T. (2009). Estimation of the hydrodynamic coefficients of the complex-shaped autonomous underwater vehicle TUNA-SAND. *Journal of Marine Science and Technology*. 14(3): 373–386.
- Thorleifson, J. M., Davies, T. C., Black, M. R., Hopkin, D. A., Verrall, R. I., Pope, A., Monteith, I., et al. (1997). The Theseus autonomous underwater vehicle. A Canadian success story. *OCEANS '97. MTS/IEEE Conference Proceedings*. vol. 2. pp. 1001-1006.
- Timmis, J., Neal, M., and Thorniley, J. (2009). An adaptive neuro-endocrine system for robotic systems. *IEEE Workshop on Robotic Intelligence in Informationally Structured Space, RIIS '09*. Page 129–136.
- Timmis, J., Murray, L., and Neal, M. (2010). A neural-endocrine architecture for foraging in swarm robotic systems. *Nature Inspired Cooperative Strategies for Optimization (NICSO 2010)*. pp. 319–330.
- Timmis, J., and Neal, M. (2004). Artificial homeostasis: Integrating biologically inspired computing. *EB/OL*. Retrieved from [www. cs. kent. ac. uk/pubs/2003/1586/content. pdf](http://www.cs.kent.ac.uk/pubs/2003/1586/content.pdf)
- Trimble, G. M. (1998). The Cetus UUV/EOD robotic work package: a low-cost shallow-water UUV system for underwater search and intervention. *OCEANS '98 Conference Proceedings*. pp. 369-373.

- Vander, A. J., Sherman, J., and Luciano, D. S. (2003). *Human Physiology: The Mechanisms of Body Function*. (E. P. Widmaier, H. Raff, & H. Strang, Eds.) (9th edition, p. 818). McGraw-Hill Education (ISE Editions).
- Varela, F., Coutinho, A., Dupire, B., and Vaz, N. N. (1988). Cognitive networks: immune, neural and otherwise. *Theoretical immunology*. 2: 359–375.
- Vargas, P., Moioli, R., de Castro, L. N., Timmis, J., Neal, M., and Von Zuben, F. J. (2005). Artificial homeostatic system: A novel approach. In M. S. Capcarrere, A. A. Freitas, P. J. Bentley, C. G. Johnson, & J. Timmis (Eds.), *Advances in Artificial Life, Proceedings*. vol. 3630. pp. 754–764.
- Van de Ven, P. W. J., Flanagan, C., and Toal, D. (2005). Neural network control of underwater vehicles. *Engineering Applications of Artificial Intelligence*. 18(5): 533–547.
- Van de Ven, P. W. J., Johansen, T. A., Sørensen, A. J., Flanagan, C., and Toal, D. (2007). Neural network augmented identification of underwater vehicle models. *Control Engineering Practice*. 15(6): 715–725.
- W. Ross Ashby. (1960). *Design for a Brain: The Origin of Adaptive Behavior* (p. 296). London: Chapman and Hall; 2nd edition.
- Wang, S., Sun, X., Wang, Y., Wu, J., and Wang, X. (2011). Dynamic modeling and motion simulation for a winged hybrid-driven underwater glider. *China Ocean Engineering*. 25(1): 97–112.
- Wang, S. X., Sun, X. J., Wu, J. G., Wang, X. M., and Zhang, H. W. (2010). Motion characteristic analysis of a hybrid-driven underwater glider. *OCEANS 2010 IEEE - Sydney*. pp. 1-9.
- Wang, W., and Clark, C. M. (2006). Modeling and Simulation of the VideoRay Pro III Underwater Vehicle. *OCEANS 2006 - Asia Pacific*. pp. 1–7.
- Wang, Y. H., and Wang, S. X. (2009). Dynamic Modeling and Three-Dimensional Motion Analysis of Underwater Gliders. *China Ocean Engineering*. 23(3): 489–504.
- Wang, Y. H., Zhang, H. W., and Wang, S. X., (2009). *Trajectory Control Strategies for the Underwater Glider*. 2009 International Conference on Measuring Technology and Mechatronics Automation. pp. 918–921.
- Webb, D C, Simonetti, P. J., and Jones, C. P. (2001). SLOCUM: An underwater glider propelled by environmental energy. *IEEE Journal of Oceanic Engineering*. 26(4): 447–452.

- Webb, D. C., and Simonetti, P. J. (1997). A Simplified Approach to the Prediction and Optimization of Performance of Underwater Gliders. 60-68 *10th International Symposium on Unmanned untethered submersible technology International symposium*. pp. 60–68.
- White, B. A. (1998). Robust control of an unmanned underwater vehicle. *Proceedings of the 37th IEEE Conference on Decision and Control*. vol. 3. pp. 2533–2534.
- Wick, C. E., and Stilwell, D. J. (2001). A miniature low-cost autonomous underwater vehicle. *OCEANS, 2001. MTS/IEEE Conference and Exhibition*. pp. 423-428
- Woithe, H. C., and Kremer, U. (2009). A programming architecture for smart autonomous underwater vehicles. *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009*. pp. 4433-4438.
- Wood, S. (2009). *Autonomous Underwater Gliders. Underwater Vehicles*. pp. 499–534.
- Wu, J. G., Chen, C. Y., and Wang, S. X. (2010). Hydrodynamic Effects of a Shroud Design For a Hybrid-Driven Underwater Glider. *Sea Technology*. 51(6): 45–47.
- Yang, H., and Ma, J. (2010a). Sliding mode tracking control of an autonomous underwater glider. *2010 International Conference on Computer Application and System Modeling (ICCASM)*. pp. 555-558.
- Yang, H., and Ma, J. (2010b). Nonlinear control for autonomous underwater glider motion based on inverse system method. *Journal of Shanghai Jiaotong University (Science)*. 15(6): 713–718.
- Yoerger, D. R., Slotine, J.-J. E., Newman, J., and Schempf, H. (1985). Robust trajectory control of underwater vehicles. *Proceedings of the 1985 4th International Symposium on Unmanned Untethered Submersible Technology*. vol. 4. pp. 184–197.
- Yuh, J. (1990). Modeling and control of underwater robotic vehicles. *IEEE Transactions on Systems, Man and Cybernetics*. 20(6): 1475-1483.
- Yuh, J. (1995). A learning control system for unmanned underwater vehicles. *OCEANS '95. MTS/IEEE. Challenges of Our Changing Global Environment. Conference Proceedings*. pp. 1029-1032.
- Yuh, J. (2000). Design and Control of Autonomous Underwater Robots: A Survey. *Autonomous Robots*. 8(1): 7–24.
- Yuh, J, and Nie, J. (2000). Application of non-regressor-based adaptive control to underwater robots: experiment. *Computers & Electrical Engineering*: 26(2): 169–179.



- Yuh, J., Nie, J., and Lee, C. S. G. (1999). Experimental study on adaptive control of underwater robots. *Proceedings of 1999 IEEE International Conference on Robotics and Automation*. pp. 393–398.
- Yuh, J. (1990). A neural net controller for underwater robotic vehicles. *IEEE Journal of Oceanic Engineering*. 15(3): 161–166.
- Zhang, S., Yu, J., Zhang, A., and Zhang, F. (2013). Spiraling motion of underwater gliders: Modeling, analysis, and experimental results. *Ocean Engineering*. 60(0): 1–13.
- Zhang, Y., Zhang, L., and Zhao, T. J. (2006). Discrete decentralized supervisory control for underwater glider. In Y. Chen & A. Abraham (Eds.), *ISDA 2006: Sixth International Conference on Intelligent Systems Design and Applications*. vol. 2. pp. 103–106.
- Zhao, S., and Yuh, J. (2005). Experimental Study on Advanced Underwater Robot Control. *IEEE Transactions on Robotics*, 21(4): 695–703.
- Zheng, J., Chen, Y., and Zhang, W. (2010). A Survey of artificial immune applications. *Artificial Intelligence Review*. 34(1): 19–34.
- Zimmer, U. R. (2006). The Australian National University - Information Engineering -Serafina. *The Australian National University*. Retrieved from <http://serafina.anu.edu.au/>