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

By

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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

τ_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

α - Angle of attack

ω_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

τ_{Db} - Damping forces on glider body

τ_{Dlw} - Damping forces on left wing

τ_{Drw} - Damping forces on right wing

τ_{Dr} - Damping forces on rudder

δ_{lw} - Deflection angle of left wing

δ_{rw} - Deflection angle of right wing

δ_r - Deflection angle of rudder

d - Diameter

C_D - Drag coefficient
m_w - Fixed point mass
τ - Forces and moments vector action on glider body
τ_{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 enegry
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

θ - Pitch angle

q - Pitch rate

A_p - Planform area

τ_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

$\emptyset$ - Roll angle

p - Roll rate

m_{py} - Rotating moving mass

$J(\eta)$ - Rotation and transformation matrix of Euler angles

δ - 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

$\widehat{\omega}_2$ - Skew-symmetric matrix of angular velocities

β - Sideslip angle

P_p - Sliding mass net forces

m_{px} - Sliding moving mass

S_b - Surface of glider body

S_r - Surface of rudder

S_w - Surface of wings

u - Surge

v - Sway

M - System inertia matrix

ω_1 - Translational velocities

r_b - Vector of ballast mass position

r_{cb} - Vector of centre of buoyancy position

r_{cg} - Vector of centre of gravity position

Θ - Vector of Euler angles

b - Vector of glider position

r_p - Vector of internal moving mass

V_c - Velocities and accelerations of water currents

V_{ch} - Volume of cylindrical hull

V_{eh} - Volume of ellipsoidal hull

∇ - Volume of glider body

ρ - Water density

W - Weight

s - Wing half-span

ψ - Yaw angle

r - Yaw rate

ALGORITMA PENGAWAL BERINSPIRASIKAN HOMEOSTATIK UNTUK PELUNCUR BAWAH AIR BERAUTONOMI YANG DIPACU SECARA HIBRID

ABSTRAK

Peluncur bawah air yang dipacu secara hibrid yang dibentangkan di dalam tesis ini menggabungkan konsep peluncur bawah air yang dipacu menggunakan daya keapungan dengan kenderaan bawah air konvensional. Ia diklasifikasikan sebagai satu jenis peluncur bawah air yang baharu. Peluncur-peluncur bawah air sedia ada yang dipacu menggunakan daya keapungan telah dibuktikan sebagai alat yang hebat dalam aplikasi oseanografi. Ini adalah kerana ia murah, mempunyai ketahanan tinggi dan jimat tenaga. Walau bagaimanapun, peluncur jenis ini masih mempunyai kelemahan dari segi kelajuan dan pergerakan yang disebabkan oleh kekurangan sistem penggerak, pergerakan yang perlahan, kekurangan daya pacuan, dan bahagian kawalan luaran yang terhad. Tambahan pula, adalah sukar untuk mengawal peluncur bawah air kerana ketidaklelurusan yang tinggi dan kerumitan dinamik peluncur, beserta dengan persekitaran dan gangguan bawah air. Oleh itu, objektif utama kajian ini adalah untuk merekabentuk dan membangunkan algoritma pengawal yang membuatkan peluncur boleh suai walaupun menghadapi kekangan-kekangan ini. Satu pengawal berinspirasikan homeostatik yang kukuh dan boleh diharap telah direka untuk tujuan ini. Pengawal ini dapat menyesuaikan diri terhadap keadaan perubahan yang dinamik dan mampu untuk pampas gangguan dari arus air. Algoritma pengawal ini telah direka berdasarkan mekanisma kawalan semulajadi manusia dengan mengintegrasikan tiga sistem buatan: rangkaian neural, sistem endokrin, dan sistem imun. Berdasarkan keputusan simulasi penandaarasan kaedah kawalan, pengawal homeostatik telah berjaya mencapai sudut anggul yang diingini dalam masa penetapan paling pantas, iaitu dengan 12.5 saat lebih pantas daripada model kawalan ramalan (MPC), 9 saat lebih pantas daripada pengatur linear kuadratik (LQR), 6.5 saat lebih pantas daripada pengawal rangkaian neural, dan 3.75 saat lebih pantas daripada pengawal neuroendokrin. Di samping itu, pengawal homeostatik telah dapat mengoptimumkan jisim balast dan jarak jisim gelongsor bagi mencapai sudut anggul yang dikehendaki dengan memendekkan jarak jisim gelonsor sehingga 53.7% dan mengurangkan jisim balast sehingga 17.7% apabila dibandingkan dengan LQR dan MPC. Secara keseluruhan, pengawal homeostatik telah mencapai prestasi terbaik berbanding dengan pengawal LQR, MPC, rangkaian neural and neuroendokrin. Tambahan pula, analisis-analisis pengesahan antara keputusan simulasi dan eksperimen telah menunjukkan bahawa sistem kawalan homeostatik menghasilkan prestasi yang sangat memuaskan, dengan pengawal homeostatik dapat mencapai sudut yang dikehendaki.

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

ABSTRACT

The autonomous hybrid-driven underwater glider presented in this thesis combines the concept of a buoyancy-driven underwater glider and a conventional autonomous underwater vehicle. It is classified as a new kind of autonomous underwater glider. The existing buoyancy-driven gliders have proven to be powerful tools in oceanographic applications. This is because they are inexpensive, high-endurance and energy-efficient. However, they still have weaknesses in terms of speed and manoeuvrability due to the under-actuated system; relatively slow; limited propulsion forces; and limited external control surfaces. Furthermore, it is difficult to control the glider because of the high nonlinearity and complexity of the glider dynamics, coupled with the underwater environments and disturbances. Thus, the main objective of this research is to design and develop a controller algorithm that is able to make the glider adaptive despite facing these constraints. A robust and reliable homeostatic-inspired controller system has been designed for this purpose. The controller is able to adapt efficiently to the dynamically changing conditions and is able to compensate the disturbance from water currents. The controller algorithm has been designed based on the human innate control mechanism by integrating three artificial systems: the artificial neural network (ANN), artificial endocrine system (AES), and artificial immune system (AIS). According to simulation results of control methods benchmarking, the homeostatic controller was able to achieve the desired pitch angle at the fastest settling time, which was 12.5 seconds faster than the

model predictive control (MPC); 9 seconds faster than the linear-quadratic regulator (LQR); 6.5 seconds faster than the neural network (NN) controller; and 3.75 seconds faster than the neuroendocrine controller. In addition, the homeostatic controller was able to optimise the ballast mass and distance of the sliding mass in order to achieve the desired pitch angle by shortening the sliding mass distance up to 53.7% and reducing the ballast mass up to 17.7% when compared with the LQR and MPC. Overall, the homeostatic controller has achieved the best performance compared with the LQR, MPC, NN and neuroendocrine controllers. Furthermore, the validation analyses between the simulation and experimental results have shown that the homeostatic control system produces very satisfactory performance, with the homeostatic controller able to achieve the desired angle.

CHAPTER 1

INTRODUCTION

1.1 Background

The oceans play an essential role in the future existence of all human beings. The bountiful oceanic resources such as food, oil, and gas have inspired humans to explore the ocean and marine environment for the benefit of mankind. Although the animate and inanimate ocean's resources are critical to human life, the ocean can also threaten human life through natural phenomena such as tsunamis and underwater earthquakes. These effects have made many researchers take progressive action to explore the full depths of the ocean resources as well as to monitor ocean activities.

In recent years, the scientific exploration of the ocean has expanded rapidly through the use of robotic technologies. Autonomous underwater vehicle (AUV) technology has been used as an important instrument in measuring and gathering oceanographic data. AUV is an untethered underwater platform that travels underwater freely with some degrees of autonomous operation. The AUV controls itself while performing a predefined mission and task, and it has an onboard power supply and other components. AUVs are able to gather many more data in a short duration than traditional methods such as expendable sensor probes and floats (Woithe and Kremer, 2009). However, the conventional propeller-driven AUVs are not suitable for a long-endurance missions due to the low efficiency in power consumption (Mahmoudian et al., 2010).

As a consequence, the interest in developing autonomous underwater gliders (AUGs) as a new breed of AUVs has experienced a substantial increase due to the high demand in long-term underwater exploration applications. Existing AUGs such as Slocum (Webb et al., 2001), Spray (Sherman et al., 2001), Seaglider (Eriksen et al., 2001), and Deepglider (Osse and Eriksen, 2007) were developed as tools for oceanographic applications. They were designed to meet the demand for underwater vehicles with low energy consumption that could be used for long-term deployment.

The typical design of the AUG is buoyancy-driven, having fixed wings, internal masses, a ballast pump, and a rudder. Thus, the buoyancy-driven AUG moves vertically through the ocean water column by controlling their pitching angle and depth through the internal masses and ballast pump, respectively. Figure 1.1 shows the motion of a buoyancy-driven autonomous underwater glider.

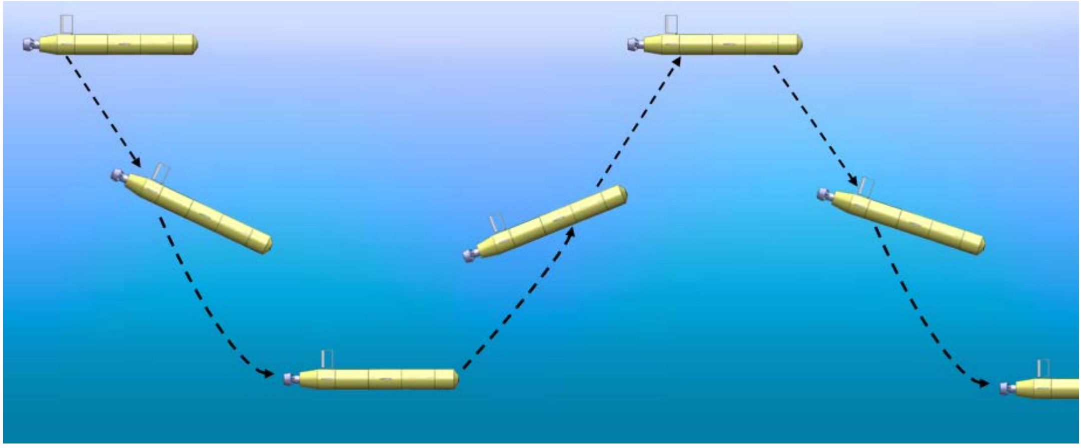

Figure 1.1: Gliding motion of autonomous underwater glider (AUG)

Although the existing buoyancy-driven AUGs have already demonstrated high energy efficiency and high endurance, these gliders still have several limitations. They are considered to be an under-actuated system; are relatively slow;

have limited external moving surfaces; and have major constraints for manoeuvring and control.

In terms of controller methods, numerous classical and modern control systems have been used to control AUVs and AUGs. Simple proportional-integral-derivative (PID) controllers and linear-quadratic regulators (LQR) have been used to control most existing gliders attitude and motion (Bachmayer et al., 2003; Kan et al., 2008; Leonard and Graver, 2001; Mahmoudian and Woolsey, 2008; Seo et al., 2008; Wang et al., 2009). The nonlinear robust control method such as sliding mode control (SMC) has also been implemented to control underwater gliders (Jun et al., 2009; Yang and Ma, 2010). However, the main drawback in SMC is the chattering effect, which can degrade the performance of the system, and may even lead to instability. Although these controller methods have already demonstrated acceptable control performance, the underwater environment imposes several restrictions on the design of the glider and its controller. Due to the nonlinearity and complexity of the glider dynamics and underwater environment, the glider should be truly autonomous, which means that it will operate steadily and adapt to its environment. In order to have those abilities, biologically-inspired control systems should be explored.

Biological systems should be considered because they are autonomous and adaptive in nature. They develop and maintain their stability and function through mechanisms such as self-organization, evolution, adaptation, and learning. Due to some limitations related to real world problems, biologically-inspired methods are a promising alternative to the classical artificial intelligence (AI) paradigm. One possible approach originates from the human biology process, known as homeostasis, which maintains a stable state in the face of massively changing conditions.

1.2 Problem Statements

The problem statements of this research work are divided into two aspects: the controller and the underwater glider platform. Thus, the problem statements of this research work are as follows:

1.2.1 *The high nonlinearity of the glider dynamics and underwater disturbances limit the controller adaptability while maintaining the overall stability*

Although researchers have previously proposed and implemented several controller methods to control AUVs and AUGs, they still face difficulties in tuning the controller gains to maintain overall stability and high quality response when the control performance degrades due to significant changes in the vehicle dynamics and its environment. The high nonlinearity and time-variance of underwater vehicle dynamics, and unpredictable underwater disturbances such as the fluctuating ocean currents are the main reasons that make it difficult to control underwater vehicles such as the underwater glider (Amin et al., 2010a; Budiyono, 2009; Yuh, 2000). Thus, it is highly desirable to design a controller that is self-tuning and has an adaptive ability to deal with these constraints.

One of the solutions is by implementing neural networks as a controller for the motion control system of the glider, due to their ability to deal with nonlinearity and to adapt to the changing conditions. Several researchers have used neural networks to control AUVs (Ishii and Ura, 2000; Li and Lee, 2005; van de Ven et al., 2005; van de Ven et al., 2007). Although the neural network has the ability to overcome the constraints, it has a low convergence rate (Bao et al., 2011). In addition, none of the previous research works have implemented neural networks to control underwater gliders.

1.2.2 *Under-actuated platform with limited external control surfaces reduces the underwater glider efficiency in terms of speed and manoeuvrability*

The existing buoyancy-driven AUGs are considered to be underwater vehicles with high energy efficiency, where the energy consumption is less than that of propeller-driven AUVs. However, AUGs have a low degree of manoeuvrability and low speed due to the limited external control surfaces and propulsion forces. These limitations make it difficult for the AUGs to follow prescribed trajectories correctly and to penetrate the massive ocean circulation and coastal currents (Wang et al., 2010). On the other hand, conventional AUVs, which are driven using a propeller, are faster than the AUGs, but they are still considered to be under-actuated vehicles with a low degree of manoeuvrability. In addition, the AUVs' endurance capability for a long deployment mission is lower than that of the AUGs, due to the low energy efficiency of the AUVs. Therefore, changing the vehicle design and configuration could increase the glider's efficiency (Jenkins et al., 2003).

1.3 Research Objectives

The main objective of this research is to design a homeostatic controller algorithm for a hybrid-driven autonomous underwater glider. Thus, the sub-objectives are:

i. To develop a mathematical model of a hybrid-driven autonomous underwater glider.
ii. To design, develop and implement a homeostatic controller algorithm of the glider motion control system for the highly nonlinear ocean environment.
iii. To design and develop the hybrid-driven autonomous underwater glider platform for oceanographic sensing applications.

1.4 Research Scopes

In order to fulfil the stated objectives, the scope of this research is divided into three phases: glider modelling and design, controller algorithm development, and prototype development. In the glider modelling and design phase, the hybrid-driven AUG has a cylindrical hull with controllable wings, a rudder, a ballast pump, internal moving mass, and a propeller. Thus, the hybrid-driven AUG can be propelled using buoyancy and/or propeller. In order to model this glider, the buoyancy-driven AUG and the propeller-driven AUG have first been modelled as a decoupled model of the hybrid-driven AUG. However, in this thesis, a coupled model is presented instead of a decoupled model, to represent the hybrid-driven AUG. These models have been mathematically modelled based on the Newton-Euler approach and the presence of water currents as a disturbance has been taken into account. Several assumptions have also been accounted for in order to model the glider mathematically. These assumptions are as follows:

i. The centre of gravity (CG) is assumed to be located slightly under the centre of buoyancy (CB) for the purpose of achieving a stable, full-submerged underwater glider.

ii. Wind shearing effects are neglected in order to model the water currents.

iii. The fixed point mass in the glider mass configuration is assumed to be zero.

iv. In order to derive the Froude-Kriloff forces, the rigid body of the glider is assumed to be neutrally buoyant and is considered a homogeneously-distributed mass.

The hydrodynamics of the hybrid-driven AUG have been estimated by using two methods: the analytical method based on the Slender-body theory and the computational fluid dynamics (CFD) method. The Slender-body theory analysis was simulated by using MATLAB^{TM}. On the other hand, Fluent^{TM} and Gambit^{TM} were used for simulating the CFD. The purpose of using these methods is to compare and analyse the accuracy of the estimated coefficients values of the glider hydrodynamics. Then, each model has been simulated by using MATLAB^{TM} in order to examine their stability, observability and controllability in an open-loop system.

In the controller algorithm phase, three artificial systems are required to design the homeostatic controller algorithm. These three systems are an artificial neural network (ANN), an artificial endocrine system (AES), and an artificial immune system (AIS). The ANN is designed as the controller backbone; the AES is designed as the weight tuner; and the AIS is designed as the optimiser. These three systems are combined into a single system to control the glider's overall motion. The algorithm has been simulated by using MATLAB^{TM}. However, in order to analyse and benchmark the performance of this controller, a performance comparison among the LQR, model predictive control (MPC), neural network (NN) control, neuroendocrine controller, and homeostatic controller has been carried out. Several limitations and considerations have been made in order to design, develop and analyse the homeostatic controller. These limitations and considerations are as follows:

i. Only the Euler angles are considered as the desired outputs.
ii. The glider position is neglected as the parameter of interest.
iii. The water currents are considered to be unmeasured disturbances, and the velocity of the water currents is assumed to be greater than zero but less than the glider velocity.
iv. Every neuron of the ANN is assumed to be affected by one artificial hormone of the AES.

Lastly, for the prototype development phase, the glider design is drawn by using Solidworks^{TM}. Then, the glider structure is fabricated, with an aluminium alloy being used as the material for the glider structure. The mechanical and electronic portion, which consists of the actuator module, motor and propeller module, controller module, power module, sensor module, and data logger module, is installed, configured and assembled into the glider structure. The system integration process is completed after the functionality of the mechanical and electronics parts have been tested independently. Then, several experimental tests of the system are conducted. The experimental testing is divided into two types: sea test and diving pool test. These tests are conducted in order to examine the performance of the glider system in terms of buoyancy, stability, operation, motion and to validate controller performance by comparing the experimental results with the simulation results.

1.5 Thesis Outline

Overall, this thesis has eight chapters and is organized as follows. **Chapter 1** presents the introduction of this research work. Section 1.1 describes the research background. The problem statements are described in Section 1.2. Section 1.3 presents the research objectives, while Section 1.4 describes the research scope in order to fulfil the research objectives. Finally, Section 1.5 presents the thesis outline.

The literature review is discussed in **Chapter 2**. The literature review extensively discusses related and significant previous research works about the AUVs and AUGs. Section 2.2 reviews the historical aspects of AUVs and AUGs. The designs and characteristics of several AUGs are presented in Section 2.3. The modelling and controller methods of the AUVs and AUGs are reviewed in Section 2.4 and Section 2.5, respectively. Section 2.6 discusses in detail the homeostasis mechanism and homeostatic control system. A summary of this chapter is presented in Section 2.7.

Chapter 3 presents the methodology of the research work, which covers the aspects of modelling, controller design, prototype development, system design, the integration process and testing. Section 3.2 describes the overall implementation process of the research work. The system design, which covers the general system architecture of the glider and the system flowchart for each driving mode, is presented in Section 3.3.

Chapter 4 extensively describes the modelling of the hybrid-driven autonomous underwater glider. Section 4.2 discusses the generic kinematics model of the glider. The dynamics model of the glider is presented in Section 4.3. Section 4.4 describes the hydrodynamics estimation of the glider. Finally, the nonlinear equations of motion for the hybrid-driven glider model are presented in Section 4.5.

Chapter 5 presents the design and algorithm of the homeostatic controller. Section 5.2 describes the overall design and framework of the homeostatic controller. Section 5.3 discusses the artificial neural network (ANN) that was designed as the backbone of the homeostatic controller. The artificial endocrine system (AES) that was designed as the weight tuner for the controller is presented in Section 5.4. Section 5.5 discusses the artificial immune system (AIS) that was designed as the optimizer for the controller. Lastly, Section 5.6 illustrates the algorithm of the homeostatic controller.

Chapter 6 presents the prototype development and system integration. In this chapter, 3D modelling of the hybrid-driven AUG via CAD software is discussed in Section 6.2. Then, the prototype development in terms of fabrication and mechanical system development is described in Section 6.3. Section 6.4 discusses the electronic components and system integration. A summary is presented in Section 6.5.

Chapter 7 presents the results and discussion of the research work. Section 7.2 discusses the simulation results of hydrodynamics estimation. Section 7.3 presents the simulation results of the homeostatic control system. In Section 7.4, the benchmarking of controller performance analysis for several controller methods including the homeostatic controller is presented. The prototype testing and experimental results in the diving pool and sea trial, which include the analysis of the real-time closed-loop system test and validation are discussed in Section 7.5. Finally, a summary is presented in Section 7.6.

Finally, conclusions of this research work and recommendations for future works are presented in **Chapter 8**.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review discusses in detail the AUV and AUG technologies; this includes a historical overview, designs and characteristics, modelling, and control methods. Additionally, the process of homeostasis and the topic of homeostatic control systems are discussed extensively. Figure 2.1 shows the overview of the literature review.

2.2 Historical Overview of AUV and AUG

The development of underwater vehicles was established a long time ago. It began with the production of the first human-controlled submarine, which was built by Van Drebbel in 1620 (Roberts and Sutton, 2006). However, this submarine was not used for naval operation. The first submarine for naval operation was built by David Bushnell in 1776 (Blidberg, 2001). However, this submarine did not operate efficiently; carbon dioxide levels rose quickly due to the air supply duration of only for thirty minutes. As a consequence of these problems, the interest in designing an unmanned underwater vehicle (UUV) increased dramatically.

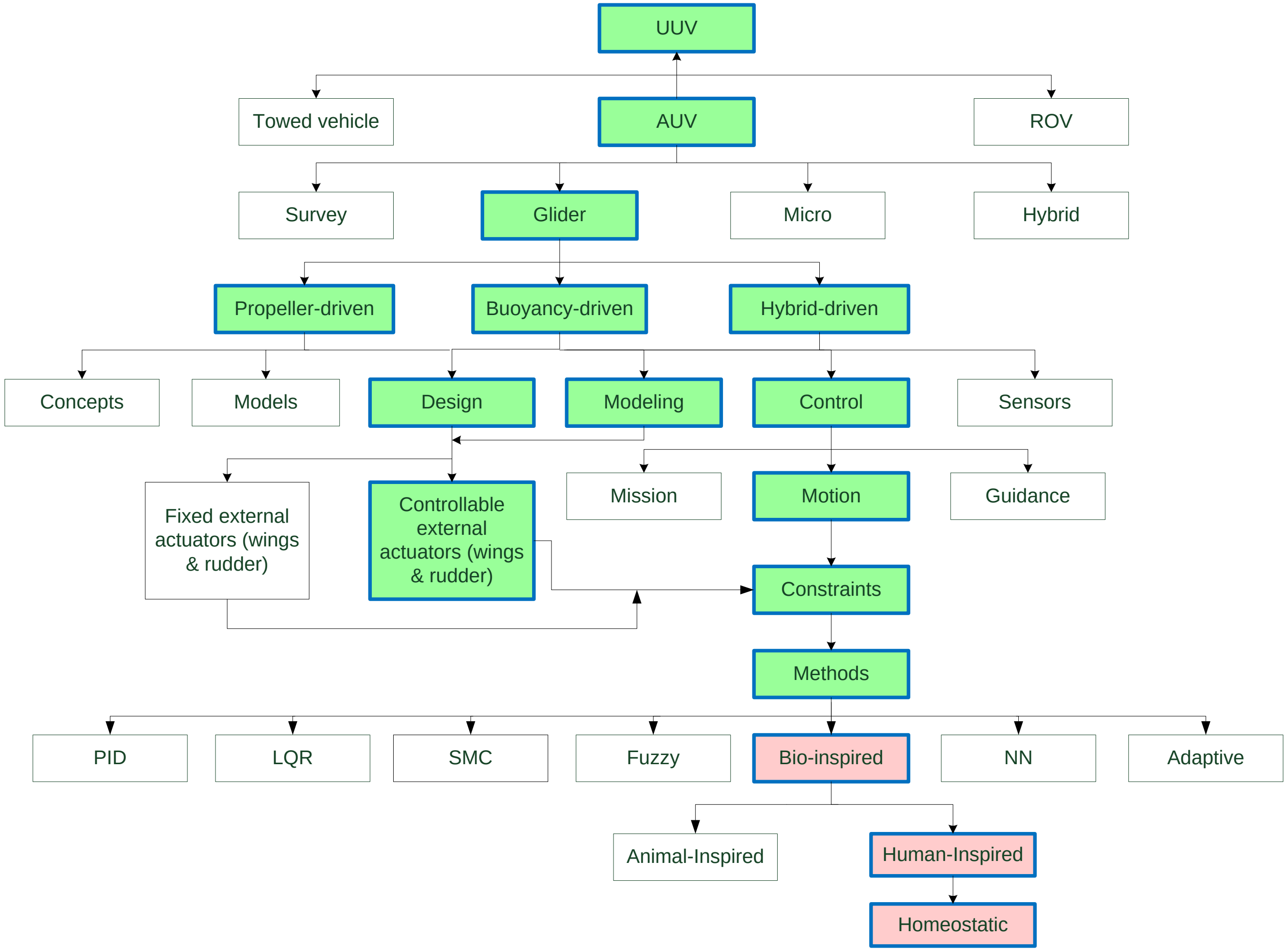

Figure 2.1: The overview of the literature review. The highlighted box indicates the focal points of this research work

An UUV is a mobile underwater robot that is able to perform tasks in areas of underwater operation that may be restricted or hazardous for humans. According to Roberts and Sutton (2006), the first UUV was designed by Whithead in 1868 as a self-propelled torpedo. Subsequently, the UUV had been commercialized in the 1970s, with commercial UUVs being divided into two classes: autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs).

ROVs have an open-frame structure and are tethered by an umbilical cable. The umbilical cable is used to supply power to the vehicle and to transfer data and commands. The ROV is the most commercial UUV. It has been used extensively to perform underwater tasks in the offshore industry such as oil and gas facility installation, oil rigs inspection, cable or pipeline inspection and lay-out, scientific sampling, search and rescue operations, and mine search in military operations. According to Christ and Wernli (2007), the ROV technology reached maturity in the 1980s and was established as commercial UUV technology by the early 1990s. However, ROVs are limited to a few applications, which are related to deeper water environments due to the very high operational costs, difficulties of handling the long cable, operator fatigue and safety issues (Yuh, 2000). As a consequence of these limitations, the demand for AUVs increased dramatically.

2.2.1 Autonomous Underwater Vehicle (AUV)

An AUV is an untethered underwater platform that travels freely with some degrees of autonomous operation. The AUV controls itself while performing a predefined task, and it has an onboard power supply and other components such as sensors. AUVs have many advantages in executing difficult underwater operations. The main advantage is that the AUV is operated autonomously, which means without human control. Thus, it is capable of performing dangerous tasks that humans are not able to do efficiently. Currently, AUVs are used for many applications such as a scientific surveys, oceanographic sampling, under-ice surveys, and military operations (Antonelli et al., 2008).

In the 1970s to 1980s, testbeds of AUVs had been developed in order to define the potential of these autonomous underwater platform systems. In the 1970s, the underwater vehicle of Unmanned Arctic Research Submersible (UARS) and Self-Propelled Underwater Research Vehicle (SPURV) were developed by the University of Washington. These vehicles were used to gather data in the Arctic region (Blidberg, 2001). Other testbeds development platforms were also fabricated, and there were some successes and many failures. The main problem was the limited computer technology available during that time.

In the 1980s to 1990s, the advancement in computer technology had tremendously increased, and it was a turning point for AUV technology. During this time, the proof of concept of the AUV prototypes was developed, tested and used. In the following decade up until the millennium, AUVs grew to become the first generation of operational vehicle systems that were able to accomplish defined tasks. Thus, many researchers attempted to develop AUVs, with a focus on various operational tasks. This progressive development created new paradigms for AUV utilization; for example, the Autonomous Oceanographic Sampling System (AOSN) (Curtin et al., 1993), and provided the resources to move this technology closer to commercialization.

After the twentieth century, the first truly commercial AUVs have become commercially available due to the demand for AUV technology for the purpose of commercial underwater applications. There were more than 46 AUV models in 1999 (Budiyono, 2009; Yuh, 2000), and today there are hundreds of different operational AUVs have been designed, most of which are experimental (Alam et al., 2014).

Initially, AUVs were very large vehicles that were torpedo-shaped or submarine-shaped. These vehicles were equipped with navigation systems, 3D Doppler velocity loggers (DVL), six degree of freedom (6-DOF) inertial measurement units (IMU), and a suite of sensors. Currently, AUVs can be divided into four categories: micro AUVs, survey AUVs, hybrid AUVs, and underwater gliders.

The micro AUV is a tiny vehicle that weighs less than 5 kg and has been developed to deploy one specific sensor at a time (Rodríguez and Piera, 2005). Several types of micro AUVs have been developed; for example, the Ranger (Hobson et al., 2001), the HUSNA-1 (Wick and Stilwell, 2001), and the Serafina (Zimmer, 2006). These AUVs share a similar function and mechanical design with the survey AUV, which was designed as a cylindrical hull with a single tail-mounted propeller. They are very small in diameter and length which is around 9 cm and 1 m, respectively. Commonly, the majority of underwater research that has focused on swarm behaviour has used the micro AUV as a platform.

Survey AUVs have a torpedo-shaped hull with a single-mounted propeller. These AUVs use hydrophones for control. Survey AUVs can be categorised as small, medium and large. The small survey AUVs, such as Remote Environmental

Monitoring Units (REMUS) (Allen et al., 1997), Fetch (Patterson and Sias, 1999) and ISiMI (Jun et al., 2009), have 1 m length and 15-20 cm diameter. These AUVs were extremely useful in several areas such as search and rescue, mapping chemical plumes, military reconnaissance, and profiling the water column of the ocean for scientific and acoustic measurements. REMUS was initially designed by Woods Hole Oceanography Institute (WHOI) and then by the HYDROID Corporation. There are over 70 REMUS designed for coastal environment operations; these vehicles cover the depth between 100 and 6000 m (Stokey et al., 2005).

Meanwhile, the medium survey AUVs have 0.5 m diameter and length of 2 m. Examples of these vehicles include Dorado (Sibenac et al., 2002), Battlespace Preparation Autonomous Underwater Vehicles (BPAUV) (Rish III et al., 2001), and Odyssey III (Damus et al., 2002). The medium size AUVs are used in various applications, which include oceanographic mapping using side scan sonar. These AUVs are designed for deep water applications that have a working depth range between 4500 and 6000 m.

Lastly, the large survey AUVs, such as the Hugin 3000 (Marthiniussen et al., 2004), Autosub (Stevenson, 1996), and Theseus (Thorleifson et al., 1997) have 1 m diameter, 10 m length, and long-range endurance capabilities of hundred of kilometres. These AUVs are used for underwater mapping, cable laying, and pipeline tracking operations. They have been designed for depths ranging from 1000 to 3000 m. For example, the Theseus AUV was developed to lay 190 km fibre-optic cable under the Arctic ice pack. This vehicle has 10.7 m length, 1.27 m diameter, displacement of 8600 kg, and 4 knots of nominal speed.

The third class of AUV is the hybrid AUV. It is a new breed of AUV that integrates the aspects of the AUV and the ROV. There are several hybrid AUVs that have been designed such as Alive (Evans et al., 2001), Swimmer (Evans et al., 2003), and Cetus (Trimble, 1998). The purpose of developing the hybrid AUV is due to some emerging applications requiring a vehicle to have rapid hovering and station keeping capabilities. For example, in some applications the vehicle needs to profile the water column vertically at a specific position. The conventional AUV cannot perform this operation. Thus, in order to have the hovering, station keeping and vertical profiling capabilities, the hybrid AUV is a suitable platform.

2.2.2 Autonomous Underwater Glider (AUG)

The AUG is the fourth and most recent class of AUV. The development of the AUG has been driven by the need to develop a low-cost, energy efficient, and autonomous underwater platform that can be used for underwater operations for long periods of time. This underwater platform evolved from the autonomous instrumented profiling floats that have been used by oceanographers for collecting oceanographic data (Graver, 2005; Rudnick et al., 2004). The floats have buoyancy actuators so that they can ascend and descend vertically, but the motion cannot be controlled because it drifts with the ocean currents once these vehicle are released.

The concept of AUG, which uses buoyancy as the propulsion system, was formally introduced in 1989 by oceanographer Henry Stommel (Stommel, 1989). Stommel and his colleague Doug Webb introduced the winged AUV that utilised a ballast system and internal moving mass to control attitude. The idea began in 1988 when Doug Webb approached Stommel with the idea of a thermally-powered glider (Eriksen, 2003; Graver, 2005). The glider was named by Stommel as Slocum after Joshua Slocum, the first man who traveled alone around the world in a small sailboat known as Spray. According to Webb, unlike the floats, a glider with wings and tail could permit the glider to glide horizontally through vertical motion and to control its position and depth. In addition, by moving the internal mass inside the glider's hull, the glider could control its pitch and roll angle. Thus, this permits the glider to ascend and descend like a float, drifting with the current, but allowing the motion and path to be controlled.

In 1990, Stommel and Webb secured a research grant to develop a battery-powered glider. The grant was awarded by the Office of Naval Technology. In 1991, the prototype of the battery-powered glider was tested in Wakulla Springs Florida and Seneca Lake New York, where the glider successfully made 29 dives in Wakulla Springs and 14 dives in Seneca Lake for a depth of 20 m (Graver, 2005; Simonetti, 1992; Webb and Simonetti, 1997). All of the main features on this battery-powered glider prototype, which had an electric buoyancy pump, fixed wings and tail, and a moving mass, can be seen in today's underwater gliders.

Thus, the concept of a buoyancy-driven underwater glider has motivated the development of several operational gliders such as the Slocum glider (Webb et al., 2001), Spray glider (Sherman et al., 2001), Seaglider (Eriksen et al., 2001), and Deepglider (Osse and Eriksen, 2007). These gliders were developed as a tool for oceanographic applications such as oceanographic sensing and sampling. These gliders have similar characteristics to the battery-powered glider prototype, which was developed by Stommel and Webb. Although they are still buoyancy-driven gliders, their size, weight and configuration are slightly different. However, each of these gliders has the same objective, which is to meet the demand for a vehicle with low power consumption that could be used for long-term oceanographic operations. Most of these gliders are 20-30 cm in diameter and not more than 2 m in length.

The concept of gliding to reduce energy while diving through the water column of the oceans is also used by marine mammals such as dolphins, seals, and whales. These animals compress their bodies and lungs to make them heavy so that they are able to glide longer and dive deeper (Graver, 2005; Mahmoudian, 2009). This concept has also inspired numerous institutes to develop underwater gliders for research purposes such as the ALBAC (Kawaguchi et al., 1993), ROGUE (Graver, 2005), Alex (Arima et al., 2008, 2009), Liberdade XRAY (Jenkins et al., 2003; Wood, 2009), WaveGlider (Wood, 2009), ITB-SGAUV (Sagala and Bambang, 2011) and USM Glider (Ali Hussain et al., 2010).

Today, the development of underwater gliders has evolved from the buoyancy-driven mechanism to the hybrid-driven mechanism, which means that the glider is able to propel itself via buoyancy and/or propeller. The first hybrid glider, which is known as STERNE, was developed at the Ecole Nationale Superieure D'Ingenieurs (ENSIETA), in Brest, France, under the French Ministry for Defense (Graver, 2005; Moitie and Seube, 2001). STERNE is designed for surveying applications by gliding using its ballast tank and moving mass, or by hovering using its thruster.

In 2004, another hybrid glider was formally introduced by Alvarez et al. (2004). This hybrid glider was named Folaga after an aquatic bird, which known as

Coot. The Folaga was designed with an actuation system that integrates the actuator set for propulsion and manoeuvring with buoyancy change and dislocation of mass (Caffaz et al., 2010). Then in 2009, a winged hybrid glider PETREL was designed and tested in Tianjin University, China (Wang et al., 2011; Wu et al., 2010). Although the power consumption of the buoyancy-driven AUG was less than that of the propelled AUV, it was obvious that the AUGs had limitations in terms of speed and manoeuvrability due to the limited propulsion forces and external control surfaces.

2.3 Autonomous Underwater Glider Designs and Characteristics

This section discusses the designs and features of the existing AUGs, which group includes the hybrid-driven AUGs. The objective of this discussion is to guide the design of the hybrid-driven AUG so that the mathematical model, controller algorithm and prototype development of the glider could be developed.

The gliding flight of existing underwater gliders such as Slocum, Spray and Seaglider is buoyancy-driven, which means that they do not use thrusters or propellers. They have a cylindrical or ellipsoidal hull with nose and tail, wings, a rudder, a ballast pump, internal moving masses, and batteries as a power system. Internal electronic components include the sensors, microcontroller, communication module and data logger.

In order to travel in a zigzag pattern through the ocean, these vehicles change depth and pitch to glide. The depth is varied by continuously controlling their buoyancy level from neutrally buoyant to negatively and positively buoyant using a ballast pump, and the pitch is changed by controlling their internal moving mass. Conventionally, existing gliders have fixed wings, and they control their attitude (such as roll and pitch) by moving their internal masses and a rudder (Graver, 2005). They are relatively slow-moving due to conserved power, so that they could be used for long-duration missions. Their maximum speeds are 0.5 knot, and most of the power is used for ballast pumping (Jenkins et al., 2003).

In this work, there are 14 AUGs that have been reviewed in terms of mechanical and electronic designs and characteristics as well as control mechanisms and performance characteristics. These AUGs are: Slocum Battery and Slocum Thermal (Bender et al., 2008; Graver, 2005; Griffiths et al., 2002; Rudnick et al., 2004; Webb et al., 2001; Wood, 2009), Spray (Bender et al., 2008; Graver, 2005; Griffiths et al., 2002; Rudnick et al., 2004; Sherman et al., 2001; Wood, 2009), Seaglider (Bender et al., 2008; Eriksen et al., 2001; Griffiths et al., 2002; Rudnick et al., 2004; Wood, 2009), Deepglider (Osse and Eriksen, 2007; Wood, 2009), ALBAC (Graver, 2005; Kawaguchi et al., 1993; Wood, 2009), Liberdade XRAY (ONR, 2006; Wood, 2009), ROGUE (Graver and Leonard, 2001; Graver, 2005; Leonard and Graver, 2001; Mahmoudian, 2009), STERNE (Graver, 2005; Griffiths et al., 2007; Hussain et al., 2011; Moitie and Seube, 2001; Wood, 2009), ALEX (Arima et al., 2008, 2009; Ichihashi et al., 2008), Folaga (Alvarez et al., 2009; Caffaz et al., 2010), PETREL (Wang et al., 2010, 2011), Tsukuyomi (Asakawa et al., 2011, 2012), and Hybrid glider (Peng et al., 2013). Table 2.1 presents the general descriptions of these AUGs.

Table 2.1: General descriptions of the AUGs

Glider Name	Developer	Year	Propulsion	Environment
Slocum Battery	WRC	1991	Buoyancy	Shallow water
Slocum Thermal				Shallow water with a thermocline
Spray	SIO	2001		Shallow water
Seaglider	University of Washington	2001		
Deepglider		2001		Deep water
ALBAC	University of Tokyo	1992	Drop weight system	Shallow water
Liberdade XRAY	SIO; University of Washington; WHOI; Bluefin Robotics; SPAWAR Systems Centre	2006	Buoyancy	
ROGUE	Princeton University	2001		
STERNE	ENSIETA		Hybrid (Propeller and Buoyancy)	
ALEX	Osaka Prefecture University	2008	Buoyancy	
Folaga	IMEDEA Institute; GraalTech; University of Pisa; University of Genova, Nato Undersea Research Centre (NURC)	2003	Hybrid (Jet-pumps and Buoyancy)	
PETREL	Tianjin University	2010	Hybrid (Propeller and Buoyancy)	
Tsukuyomi	Japan Agency for Marine-Earth Science and Technology; Kyushu University;	2012	Buoyancy	Deep water
Hybrid glider	Zhejiang University	2013	Hybrid (Rotatable Thruster and Buoyancy)	Shallow water

In Table 2.1, the environment of the operational glider is divided into two: shallow water and deep water. Generally, the depth range of shallow water is up to 1500 m and the depth range of deep water is greater than 1500 m (Wood, 2009). Previously, there were several researchers have developed hybrid-driven underwater gliders. However, these researchers have either developed a hybrid-driven glider with no wings (Alvarez et al., 2009; Caffaz et al., 2010) or fixed wings (Wang et al., 2010, 2011). Thus, these gliders are considered have a low degree of manoeuvrability due to the limited external control surfaces such as controllable wings and rudders.

2.3.1 Mechanical Designs and Characteristics

The review of the mechanical designs of the AUGs covers the hull, wings, rudder or vertical stabiliser, weight and payload. Table 2.2 presents the mechanical designs and characteristics of the AUGs. Basically, most of the reviewed underwater gliders, except the Liberdade XRay, have a cylindrical shape. The length of the hull of these gliders is between 1 m to 4.5 m, and the range of the hull's diameter is between 20 cm to 60 cm. Meanwhile, the range of the weight is between 10 kg to 900 kg. Most of these gliders have fixed wings and vertical stabiliser (rudder). The wings provide hydrodynamic lift to propel the vehicle forward as it descend and ascend.

Although these gliders have similar mechanical design, the characteristics are slightly different. The purpose of changing the glider design, characteristic and configuration is to increase the glider efficiency. As an example, the design of Spray is similar to the Slocum Battery. However, it has better hydrodynamic shape, which produced fifty percent less drag than the Slocum Battery (Sherman et al., 2001; Wood, 2009). As another example, the design of Deeglider is similar in size and shape of the Seaglider but has more weigh and displacement. It uses composite pressure hull of carbon fibre and thermoset resin, making it capable of diving up to 6000 m (Osse and Lee, 2007; Wood, 2009). Thus, by changing the glider design, characteristic and configuration, the glider efficiency could be increased.

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