BACKSTEPPING INTEGRAL SUPER TWISTING SLIDING MODE CONTROL ALGORITHM FOR AUTONOMOUS UNDERWATER GLIDER

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by

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LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
ARCS	Autonomous and Remote Controlled Submarine
AUG	Autonomous Underwater Glider
AUSI	Autonomous Undersea Institute
AUV	Autonomous Underwater Vehicle
BISTSMC	Backstepping integral Super twisting Sliding Mode Control
CB	Centre of Buoyancy
CG	Centre of Gravity
CFD	Computational Fluid Dynamic
DOF	Degree-of-Freedom
DSMC	Dynamic Sliding Mode Control
EAVE	Experimental Autonomous Underwater Vehicle
EOM	Equation of Motion
FOSMC	First Order Sliding Mode Control
FLC	Fuzzy Logic Control
GA	Genetic Algorithm
HOSMC	Higher Order Sliding Mode Control
ISMC	Integral Sliding Mode Control
ISTSMC	Integral Super twisting Sliding Mode Control
LQR	Linear-Quadratic Regulator
MMS	Marine Systems Simulator
MPC	Model Predictive Control
NDRE	Norwegian Defence Research Establishment

NN	Neural Network
NDO	Nonlinear Disturbance Observer
PD	Proportional-Derivative
PI	Proportional Integral
PID	Proportional-Integral-Derivative
PSO	Part Swarm Optimisation
REMUS	Remote Environmental Monitoring Units
RMSE	Root Mean Square Error
ROV	Remotely Operated Vehicle
SAUV	Solar Autonomous Underwater Vehicle
SIFLC	Single Input Fuzzy Logic Controller
SISO	Single-Input-Single-Output
SMC	Sliding Mode Control
SMCB	SMC based on boundary layer
SMCS	SMC based on saturation function
SODMN	Self-Organization Direction Mapping Network
SONCS	Self-Organizing Neural-net Control System
SOSMC	Second Oeder Sliding Mode Control
SPURV	Self-Propelled Underwater Research Vehicle
STSMC	Super twisting Sliding Mode Control
UARS	Unmanned Arctic Research Submersible
UV	Underwater Vehicle
UUV	Unmanned Underwater Vehicle
WHOI	Woods Hole Oceanography Institute

LIST OF SYMBOLS

α	Angle of attack
m_b	Ballast point mass
u_b	Ballast pumping rate
w_1	Control acceleration of internal movable mass in x axis
u_{aug1}, u_{aug3}	Control force on internal movable mass in x and z axes
w_{11}, w_{21}	Discontinuous control law for BISTSMC application in AUG
D	Drag
C_D, C_{DO}	Drag coefficients
m_{em}	Excess mass (net buoyancy) of AUG
m_w	Fixed point mass
g	Gravitational acceleration
v_3	Heave
m_h	Hull mass
J_1, J_2, J_3	Inertia of AUG
m_i	i^{th} diagonal element of total mass
u_i	i^{th} control law for BISTSMC
u_{i1}	i^{th} discontinuous control law for BISTSMC
u_{i0}	i^{th} nominal control law for BISTSMC
s_i	i^{th} sliding surface
δ_k	k^{th} bounded matched perturbation
e_k	k^{th} tracking error
ρ_k	k^{th} upper bounded matched perturbation
$K_{\omega_2^{1,}}, K_{\omega_2^2}$	Linear and nonlinear quadratic damping constant coefficients
m_p	Internal moving mass of AUG

L	Lift
C_L, C_{LO}	Lift coefficients
C_M, C_{MO}	Moment coefficients
w_{10}, w_{20}	Nominal control law for BISTSMC application in AUG
ω_2	Pitch rate (AUG)
θ	Pitching angle
M_{DL2}	Pitching moment
ω_1	Roll angle
R	Rotation matrix
w_2	Same as u_b
α_1	Stabilising function for BISTSMC
β	Sideslip angle
P_p	Momentum of internal movable mass
P_{p1}	Momentum of internal movable mass in x-axis
P_{p3}	Momentum of internal movable mass in z-axis
v_1	Surge
r_b	Vector of ballast point mass
r_p	Vector of internal movable mass
r_{p1}	Vector of internal movable in x-axis
r_{p3}	Vector internal movable mass in z-axis
ω_3	Yaw angle

ALGORITMA PENGAWAL KAWALAN MOD GELANGSAR KAMIRAN PIUHAN LANGKAH MENGUNDUR UNTUK PELUNCUR BAWAH AIR BERAUTONOMI

ABSTRAK

Peluncur bawah air berautonomi (AUG) menunjukkan ketidaklelurusan yang tinggi dan kerumitan dalm model dinamiknya beserta dengan persekitaran dan gangguan bawah air. Dengan penggerak yang terhad, pilihan yang dimiliki oleh AUG dalam menghadapi persekitaran dan gangguan sedemikian adalah dengan menggunakan strategi-strategi algoritma kawalan. Atas sebab ini, objektif utama penyelidikan ini adalah untuk membina hukum kawalan yang mempunyai keupayaan dalam menghadapi gangguan luar dan ketidakpastian akibat pekali hidrodinamik. Oleh itu, pengawal tegar tak lelurus telah direka dengan menggunakan algoritma pengawal kawalan mod gelangsar kamiran piuhan lampau langkah mengundur (BISTSMC) untuk model tak lelurus bagi satah membujur AUG. BISTSMC telah diuji dengan gangguan luar dan perubahan parameter. Penanda aras BISTSMC telah dibuat dengan strategi-strategi pengawal mod gelangsar yang lain bagi melihat prestasinya dalam penindasan kadar gelatuk. BISTSMC telah ditanda aras dengan pengawal mod gelangsar kamiran (ISMC), pengawal mod gelangsar piuhan lampau (STSMC), pengawal mod gelangsar piuhan lampau kamiran (ISTSMC), pengawal mod gelangsar kamiran langkah mengundur (BISMC) dan pengawal mod gelangsar piuhan lampau langkah mengundur (BSTSMC). Hasil simulasi telah menunjukkan bahawa pengawal yang dicadangkan menghasilkan kadar gelatuk terkecil lebih kurang 100 kali lebih kecil daripada ISTSMC, 10000 kali lebih kecil daripada langkah mengundur ISMC dan langkah mengundur STSMC dalam kes namaan, kes gangguan luar dan kes perubahan parameter. Ralat keadaan mantap bagi pengawal

yang dicadangkan ini juga menghasilkan ralat keadaan mantap terkecil iaitu empat kali lebih kecil daripada ISTSMC dan langkah mengundur ISMC dan dua kali lebih kecil daripada langkah mengundur STSMC dalam semua kes untuk sudut anggul dan 1000 kali lebih kecil daripada ISTSMC dan 100 kali lebih kecil daripada langkah mengundur ISMC dan langkah mengundur STSMC untuk jisim lebihan. Pengawal yang dicadangkan adalah merupakan kaedah penindasan gelantuk yang baharu yang menghasilkan ralat keadaan mantap terkecil dan gelantuk telah ditindaskan dalam semua kes.

BACKSTEPPING INTEGRAL SUPER TWISTING SLIDING MODE CONTROL ALGORITHM FOR AUTONOMOUS UNDERWATER GLIDER

ABSTRACT

The autonomous underwater glider (AUG) demonstrates highly nonlinear and complexity in its dynamic model and also coupled with external underwater environment and disturbance. With limited actuators, the only option that AUG has in facing such environment and disturbances is by using strategies of control algorithm. For this reason, the main objective of this research is to formulate the control law that has the capability in facing the external disturbances and uncertainties due its hydrodynamics coefficients. As a result, a robust and reliable has been designed using back-stepping integral super twisting sliding mode control algorithm (BISTSMC) for nonlinear model of longitudinal plane of an AUG. The BISTSMC was tested for external disturbance and parameter variations. The BISTSMC has been benchmarked its performances with other sliding mode control (SMC) strategies to evaluate the chattering suppression of the controllers. The BISTSMC was benchmarked with integral SMC (ISMC), super twisting SMC (STSMC), integral STSMC (ISTSMC), back-stepping ISMC and back-stepping STSMC. The simulation results have shown that the proposed controller provides the smallest chattering about more than 100 times smaller than ISTSMC, more than 10000 times smaller than backstepping ISMC and backstepping STSMC in nominal, disturbance and parameter variation cases respectively. The steady error of the proposed controller also gives the smallest steady state error of four times smaller than ISTSMC and backstepping ISMC and two times smaller than backstepping STSMC in all cases for pitching angle and 1000 times smaller than ISTSMC and 100

times smaller than backstepping ISMC and backstepping STSMC for excess mass. The proposed controller is a new chattering suppression method which provides the smallest steady state error and chattering has been also suppressed in all cases.

CHAPTER 1

INTRODUCTION

1.1 Background

The underwater robotic researches have received great attention since the past three decades. The robotic technologies have helped the researchers in expanding the scientific underwater exploration such as scientific ocean exploration, surveillance, commercial inspection of undersea facilities and military operations. Generally, underwater vehicle (UV) is divided in two main categories which are manned and unmanned underwater vehicles (UUVs). The UUV is further divided into remote operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). The classification of UVs is summarised in Figure 1.1. The autonomous underwater glider (AUG) is considered as a special class of AUVs.

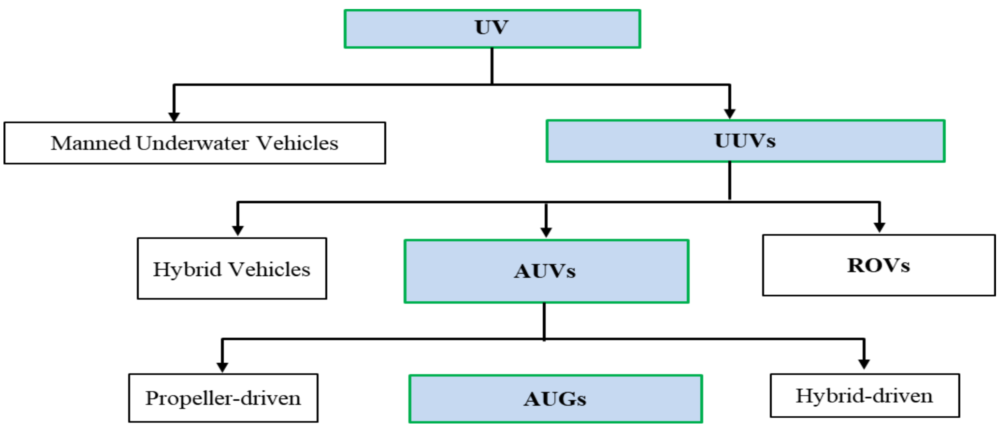

Figure 1.1 The classification of underwater vehicles (Md Zain, 2012)

The underwater glider was inspired by Henry Stommel (1989), called Slocum float. A decade later, three operational gliders namely Slocum (Webb et al., 2001), Spray (Sherman et al., 2001) and Seaglider (Eriksen et al., 2001) were developed and tested, and their performance was proven.

The basic design of the AUG is buoyancy-driven with fixed wings and rudder, internal masses and a ballast pump. The AUG glides through the water column by shifting the internal movable mass in translational or rotational depending on the design of the movable tracks and pumping of the ballast pump. By doing these, the pitching angle and the depth can be controlled and cause the AUG to glide in saw-tooth pattern. Figure 1.2 shows the ideal gliding of a buoyancy-driven AUG.

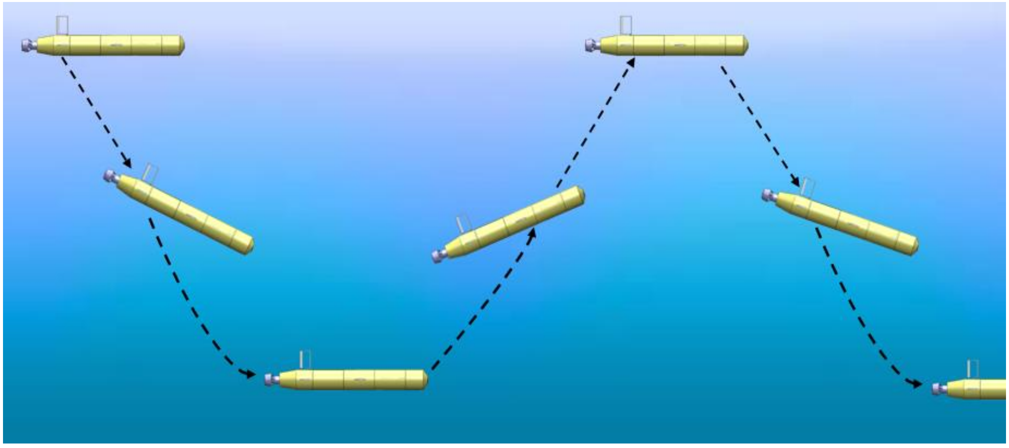

Figure 1.2 Gliding motion of AUG (Isa, 2015)

There are many control techniques either classical control or modern control have been employed to control AUVs and AUGs beginning from the simple proportional-integral-derivative (PID), linear-quadratic-regulator (LQR), robust control approach, adaptive control up to intelligent control such as fuzzy logic and neural network (NN). Among all the controllers, PID and LQR are widely used to control the existing gliders motion and attitude (Bhatta & Leonard, 2002; 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 mode predictive control (MPC) is another technique used to control the underwater gliders (Tatone et al., 2009; Shan & Yan, 2013; Abraham & Yi, 2015). However based on the survey done by Bemporad & Morari, (1999) the main problem when implementing MPC is it requires a simplified prediction model since it is model-based technique and it also needs full state of estimations which can degrade the performance of the system and may lead to instability. All control methods mentioned have demonstrated acceptable control performance. However, there is a room to improve the tracking performance of the parameters under study (control).

The sliding mode control (SMC) is one of the candidates that can be considered to improve the tracking performance of the parameters under study (control). Although the conventional SMC has suffered internally with chattering issues, however when the chattering phenomena is remedied, then the SMC is able to handle the parameter variation issue and offer the robustness towards external disturbances and uncertainties which are proven through many applications in many other systems (Jalani et al., 2010; Rhif, 2012; Li et al., 2013; Ismail et al., 2015; Heng et al., 2017; Tayebi-haghighi, 2018). In this study the chattering phenomena is reduced through integration of back-stepping, integral SMC (ISMC) and super twisting SMC (STSMC) approach.

1.2 Problem Statement

The problem statement of this research is

The AUG is considered as an under-actuated system with high nonlinearity of dynamics, with uncertainties in hydrodynamic coefficients and with the presence of underwater disturbance (J. Yuh, 2000; Pan & Xin, 2012). Therefore, a robust nonlinear controller algorithm is required to maintain the overall performance of the AUG.

Previous researchers have proposed and implemented various control techniques to control AUVs and AUGs. The performance of the controllers degrades with the changes. Therefore, it is highly desirable to design a controller that is able to reject perturbations due to plant uncertainties and external disturbances.

1.3 Research Objectives

The main objective of this research is to propose the nonlinear controller models of namely backstepping integral super twisting sliding mode control (BISTSMC) for an AUG. Thus, the sub-objectives are:

i) To formulate the control law based on BISTSMC controller algorithm.

ii) To design and apply the proposed controller in the glider motion control system.

iii) To benchmark the proposed controller algorithms performances by comparing the rate of chattering reduction of this proposed work towards disturbance rejection and parameter variations with other family of SMC strategies.

1.4 Research Scopes

The scope of the research work focuses on controller algorithm design and development, the controller benchmarking and the controller validation by using MATLAB/Simulink. The research scopes are defined as follows:

i) The simulation is restricted to longitudinal plane.

ii) The simulations are based on parameters adopted from Graver, (2005).

iii) The internal mass moves along x-axis only.

iv) The control input of the AUG is the acceleration of the internal movable mass and the ballast pumping rate.

v) The performance of the proposed controller is benchmarked with family of the SMC control strategies.

vi) The controller parameters are heuristically tuned.

vii) The perturbation is restricted to external disturbance and parameter variations only.

viii) The pitching angle and net buoyancy are selected as the observed outputs to evaluate the effectiveness of the proposed controller algorithm.

1.5 Thesis Outline

This thesis comprises of seven chapters which are organised as follows. Chapter 1 presents the introduction of this research work. Section 1.1 describes the research background. The problem statement is described in Section 1.2. Section 1.3 presents the research objectives, Section 1.4 describes the research scope in order to fulfil the research objectives and Section 1.5 presents the thesis outline.

Chapter 2 discusses the literature review. An extensive review on control strategies applications in AUVs and AUGs are discussed including the historical development of AUG related previous works. The historical developments of AUVs and AUGs are reviewed in Section 2.2. The modelling of AUGs is presented in Section 2.3. Section 2.4 reviews various control methods. Section 2.5 presents the SMC system application. The gap analysis of the controllers is discussed in Section 2.6. Finally, the whole Chapter 2 is summarised in Section 2.7.

Chapter 3 presents the modelling of the nonlinear system of AUG. Chapter 4 presents the problem formulations, the detail derivation of the control law for the proposed controller and the benchmarking. Section 4.1 presents the problem formulations of the nonlinear systems. The derivation of nonlinear control laws is discussed in Sections 4.2, 4.3 and 4.4 respectively. The design of control laws for benchmarking controllers are presented in Section 4.5. Finally, Chapter 4 is summarised in Section 4.6.

In Chapter 5, an extensive discussion of the results is presented. Section 5.1 gives introduction of Chapter 5, Section 5.2 presents the result analysis of the proposed nonlinear controller. The performances of the proposed controller are compared to performances of other selected controllers in the family of SMC to evaluate the effectiveness of the proposed controller as discussed in Section 5.3 and Section 5.4 summarises Chapter 5. Finally, Chapter 6 provides the conclusions of this research work, the recommendations proposed for the future works and contributions of the research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive review on AUVs and AUGs that includes a historical development, modelling and control strategies. An extensive discussion on the SMC will be focused on chattering phenomena reduction. The flow of literature review is shown in Figure 2.1.

2.2 Historical Development of AUV and AUG

The UVs establishment started with the development of submarine vehicle which the first submarine was built in 1620 by Van Drebbel (Roberts & Sutton, 2006) even though it was not used for naval operation. In 1775, David Bushnell built the first American sub-marine which was named as ‘Turtle’. Turtle was the first submarine used for naval operation in 1776. However, the first AUV was built in 1957 at Physics Laboratory, University of Washington which was named as SPURV (Special Purpose Underwater Research Vehicle) for data gathering in Artic region (Gafurov & Klochkov, 2015). The AUVs are used for mapping and monitoring the marine environment such as detecting and mapping submerged wrecks, rocks, conductivity, turbulence, pollutants, dissolved oxygen content and temperature. The data gained are very useful for meteorologists to predict the weather events such as El-nino and hurricanes.

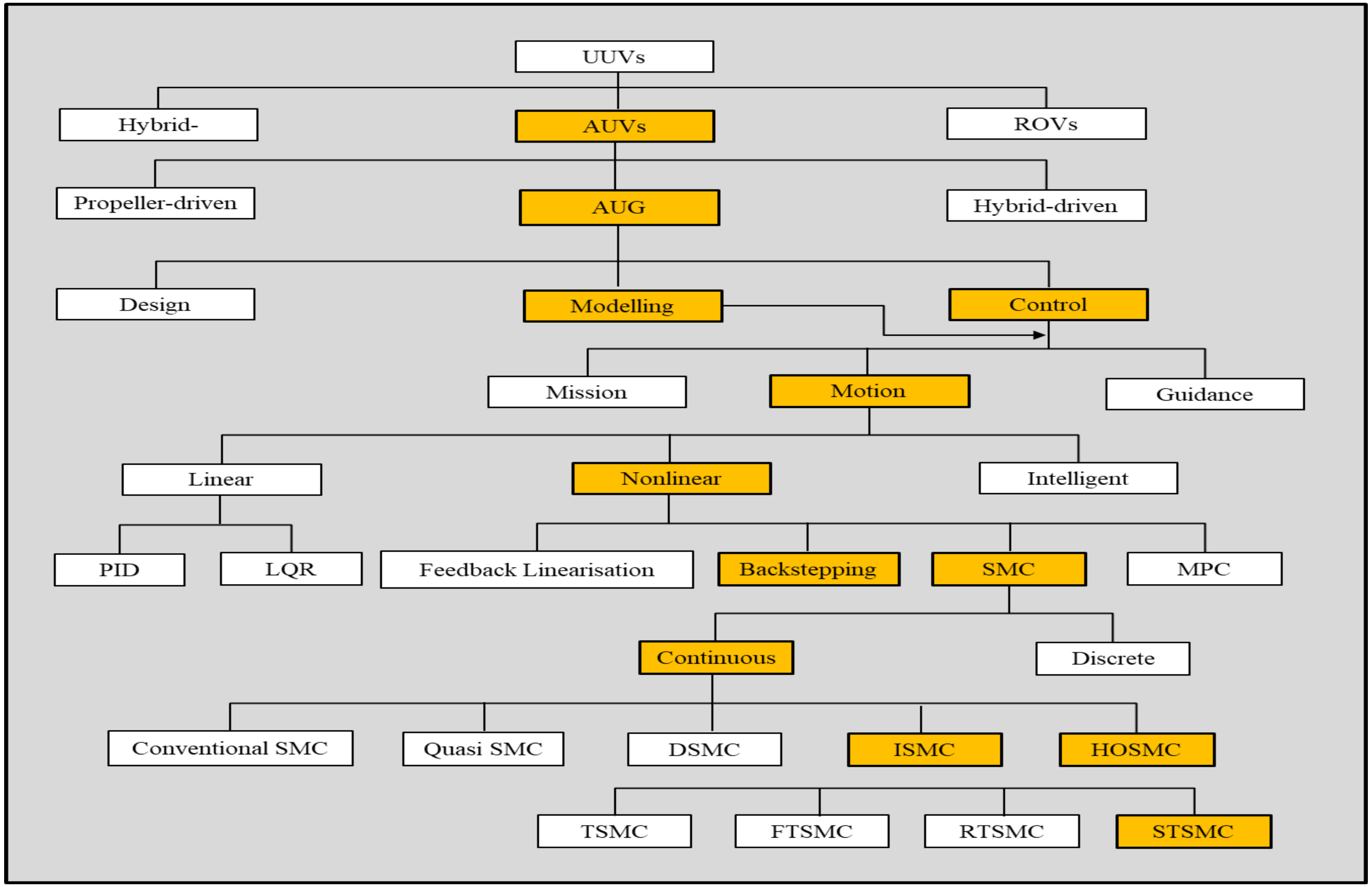

Figure 2.1 The overview of the literature review. The highlighted boxes indicate the focal points of this research work

An AUV is an untethered UV that freely travels in the water column without operator or human intervention as it controls itself when performing a predefined task. It becomes the main advantage of AUVs over ROVs. Therefore, AUVs are very suitable for performing dangerous task in hazardous environment. The AUV is equipped with an on-board power supply, sensors and other supporting equipment.

Within 1970s to 1980s, a number of AUVs was developed and tested such as Unmanned Arctic Research Submersible (UARS) and SPURV II developed by University of Washington (Blidberg, 2001). With the advancement in computer technology, there were many operational AUVs built in 1980s to 1990s. The Autonomous and Remote Controlled Submarine (ARCS) AUV was built in 1983 by ISE Ltd. company together with the Canadian Hydrographic Service and the Department of Defence which used 32-bit Motorola processor to enable the real time monitoring and controlling of the ARCS. The ARCS dived for the first time in 1987 (Gafurov & Klochkov, 2015). Also in 1987, the third version of experimental autonomous vehicle (EAVE-III) was built by Marines Systems Laboratory, University of New Hampshire (Jalbert et al., 1988). Later in late 1990s, Russian Institute of Marine Technology together with Autonomous Undersea Institute (AUSI) built the AUV that was powered by the solar panels installed on the AUV and the AUV was named as solar autonomous underwater vehicle (SAUV) (Gafurov & Klochkov, 2015).

Other than ocean environment data gathering, AUVs are also used for search and rescue operations such as remote environment units (REMUS), Hugin AUV, Autosub AUV, and Theseus AUV (Murphy et al., 2008). The REMUS was built by Woods Hole Oceanographic Institution (WHOI). A series of REMUS was built and tested ranging from REMUS 100 with 36 kg weight that dived up to 100 meters depth to REMUS 6000 with 700 kg weight which dived up to 6000 meters in depth (Stokey et al., 2005). The Hugin AUV was developed by Kongsberg Simrad, and the Norwegian Defence Establishment started with Hugin I built in 1997 for offshore survey (Marthiniussen et al, 2004). Later a number of Hugins AUVs was developed and tested starting from Hugin 1000 with the weight ranging from 650 – 850 kg that dived up to 3000 meters depth. The latest version of Hugin is Hugin 4500 with the weight of 1900 kg that dives up to 4500 meters depth (Kongsberg, 2017). The Autosub AUV was the result of the Natural Environment Research Council project that was hosted by the Southampton Oceanography Centre, UK which was aimed to have work endurance for several days that dived up to 6000 meters depth (Stevenson, 1996). However, the final result of this Autosub was that the Autosub was only able to dive up to 3000 meters (Murphy et al., 2008). Other than this, another Autosub AUV named as Theseus was built to lay up about 220 km of the fibre optic cable in the Canadian Artic Islands. It was designed with 8600 kg weight and able to dive up to 2000 meters with 1360 km endurance (Thorleifson et al., 1997).

Recently, more than hundreds different operational AUVs are built and tested (Alam et al., 2014). The size of the AUVs also reduces from very large vehicle initially, to small vehicle called micro AUV with weight less than 5 kg such as Ranger (Hobson et al., 2001), HUSNA-1 (Wick & Stilwell, 2001) (Wick & Stilwell, 2001) and Serafina (Zimmer, 2006). These micro AUVs are commonly used for underwater research that focusing on the swarm behaviour.

The AUG is a sub-class of AUV as shown in Figure 1.1 which is considered as the most recent class of AUV. The demand of the AUV with lower energy consumption, low-cost involvement and able to deploy for long endurance has resulted in development of the AUG. The idea of AUG began with the autonomous profiling float for collecting oceanographic data. The float is a buoyancy driven instrument where it can descend and ascend vertically due to the changing of the buoyancy. 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 endurance. This underwater platform is evolved from the autonomous instrumented profiling floats that have been used by oceanographers for collecting oceanographic data (Graver, 2005; Rudnick et al., 2004). The float works by using buoyancy actuators to move vertically ascending and descending. However, the motion of the float cannot be controlled because ocean current will drift it away once it is released to the ocean.

The concept of AUG uses buoyancy as the propulsion system which was introduced by oceanographer Henry Stommel (1989). In 1990, the Office of Naval awarded a research grant to Stommel and Webb for developing a battery-powered glider. The prototype of the glider was tested in Wakulla Springs Florida and Seneca Lake New York. The glider successfully completed a total of 42 dives in which 29 dives were executed in Wakulla Springs and 14 dives were carried out in Seneca Lake. (Graver, 2005; Simonetti, 1992; Webb & Simonetti, 1997). This achievement made by Stommel and Webb has motivated other researchers to involve in AUG research. As the result, in 2001 three operational gliders were developed which are named as Slocum glider (Webb et al., 2001), Spray glider (Sherman et al., 2001) and Seaglider (Eriksen et al., 2001). More recent development of glider was developed by Osse & Eriksen (2007) for endurance in deeper water.

Many laboratory scale AUGs have been developed for research purposes such as 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 & Bambang, 2011) and USM Glider (Ali Hussain et al., 2010).

Recent development of AUGs has started to evolve in hybrid-driven AUGs. The first hybrid AUG named as STERNE was developed by the Ecole Nationale Superieure D'Ingenieurs (ENSIETA) for surveying application (Graver, 2005). Later many other hybrid-driven AUGs were developed such as Folaga in 2004 (Alvarez et al., 2009), PETREL in 2009 was developed by University of Tianjin (Wang et al., 2011) and PETREL-II which was also developed recently (Wang et al., 2017).

2.3 Modelling of AUG

The mathematical model of the AUG must be established before the controller can be designed. The mathematical model of an AUG was derived by (Graver et al., 1998). The detail derivation was published in (Leonard & Graver, 2001) and (Graver, 2005). The model was derived for the ROGUE AUG which was a laboratory scale AUG that was developed at University of Princeton. The mathematical model was derived for the fixed wings and rudder with the internal movable mass moves in translational motion. Later many research works are made based on the Graver’s model such as Yang & Ma (2010a, 2010b), Bhatta & Leonard (2002), Bhatta (2006) and Ullah et al., 2016)

Mahmoudian, (2009) had established the mathematical model for AUG which its internal movable mass moved in translational and rotational (cylindrical). In the same year, Arima et al. (2009) established a model for independently controllable wing AUG named as ALEX, however there was no derivation details shown. The mathematical model winged hybrid-driven PETREL was presented in (Wang et al., 2010) for fixed wings and rudder, and the model of PETREL II was presented in Wang et al. (2017) for controllable wings.

Isa et al. (2014) presented the mathematical model for the hybrid-driven USM AUG which was derived based on the Newtonian theory which the hydrodynamics parameters were estimated using strip body theory. Another hybrid AUG mathematical model was presented by Zhang et al. (2012) and Zhang (2014). It was the hybrid AUG called as robotic gliding fish which the hydrodynamic parameters were estimated using computational fluid dynamic (CFD) software and the model was derived using the Newtonian theory.

Although many mathematical models have been previously presented, however, most the models were derived based on the model presented by Leonard & Graver (2001) and the detail derivation was made by Graver (2005).

2.4 Control Techniques of the AUV and AUG

For UVs to manoeuvre autonomously, the control algorithm must be robust against perturbations and parameter variations. It is known that the UVs are difficult to control since their system is highly nonlinear and the dynamics of the vehicles are time-varying. The hydrodynamics coefficients are uncertain, mostly disturbed by water current and also changes in centre of buoyancy (CB) and centre of gravity (CG) due to the internal actuators (Budiyono, 2009; Yuh, 2000). There have been various control techniques proposed to control the AUVs and AUGs. The control techniques to control the AUVs and AUGs are divided into three main categories; linear control, nonlinear control and intelligent control strategies. This section covers the literatures of SMC applications to cover wide spectrum of literatures. In addition to this, gap analysis of the controllers applications in AUG will be covered too to give clearer view of the research contribution.

2.4.1 Linear Control Strategies

Linear control is used when the model of the plant is linearised about the equilibrium. In underwater vehicle, the linear control is dominated by the proportional-integral-derivative (PID) and linear quadratic regulator (LQR).

PID control was used in early 1940s when the process control emerged (Karl Johan, 2002). It is simple feedback control architecture and it is also known as classical control. PID controller tries to maintain the output to be at the desired level by minimising the error by enforcing a control signal so that the actual value meets the desired value. The performance of the PID relies on three gains that are proportional, integral and derivative terms. The gain of the PID controller can be precisely estimated if the plant parameters are known using Cohen-Coon method for open-loop test, Ziegler-Nichols or Tyreus-Luyben method for closed-loop system. The easiest way with no calculation involvement is manual tuning using previous experience. However, all these three gains have to be balanced for achieving the expected performance and need to compromise the transient response.

In UVs, the PID control was employed by many researchers in their work such as Bhatta & Leonard (2002) and Mahmoudian & Woolsey (2008), were proposed for AUGs and Chellabi & Nahon (1993), Jalving (1994), Lee et al. (2009), Santhakumar & Asokan (2010), Watson & Green (2014) and Mohd Aras et al. (2017) for AUVs. Bhatta & Leonard (2002) employed proportional-integral (PI) control law to control the internal movable sliding mass and proportional control law to control the net buoyancy of ROGUE AUG. Mahmoudian & Woolsey (2008) employed PID in the AUG internal actuator (i.e. internal movable sliding mass and the ballast mass). The controller was designed for the linearised model of the dynamic equations and computed the transfer function for input-output channel of interest which produced the single-input-single-output (SISO) transfer function for the respective input-output of interest. The proportional control law was to control the ballast mass and PID control law to control the internal movable AUG. By employing the combined proportional control law and PID, the position of the internal movable sliding mass (lateral and vertical masses), glide angle and heading rate were nicely controlled.

The first implementation of PID in AUVs was proposed by Chellabi & Nahon (1993). Nonlinear dynamics of the AUV were linearised and decoupled into six SISO second-order subsystems. A combined strategy of a proportional-derivative (PD) controller and LQR was proposed for the six SISO subsystems. The PD control law was designed to stabilise the system and LQR was used to cater the optimal error correcting term for improving the robustness of the PD controller. Following this first implementation, Jalving (1994) proposed a PID controller for Norwegian Defence Research Establishment (NDRE) AUV. The nonlinear dynamics were linearised and decoupled into three subsystems which were speed, steering and diving subsystems. The speed subsystem was controlled using PI control law and this PD control law was utilised to control heading and depth. In the unmanned underwater test vehicle, Lee et al. (2009) proposed a PID controller for Manta-type unmanned underwater test vehicle to control steering and diving based on linearised model. In 2010, Santhakumar & Asokan (2010) proposed a self-tuning PID to enhance the performance of the original PID. In this work, Taguchi's method was used to build the self-tuning PID algorithm. The self-tuning performance was compared with tuning method proposed by Ziegler-Nichols. Other than these, in 2014, Watson & Green (2014) proposed a PID for micro AUV to control depth. The continuous PID was discretised using Tustin approximation to compute the discrete version of PID controller. Recently, Mohd Aras et al (2017) proposed PID controller to control heading. The PID controller is usually designed using the standard block available in MATLAB/SIMULINK and thus the gains are tuned using auto tune command. However, the proposed PID is sensitive to uncertainties and external disturbances.

Many research works have employed LQR in their works because of simple architecture of the LQR design which there are only two design parameters must be tuned so that the controlled parameters are stabilised at the equilibrium points. The LQR algorithm application in AUVs and AUGs are included in the work made by Leonard & Graver (2001), Wang et al. (2009), Isa & Arshad (2012), Javaid et al. (2015), Kan et al. (2008), Joo & Qu (2015), Reshmi & Priya (2016), Tchilian et al.

(2017), Daniel & Decio (2009) and Syahroni et al. (2008). The design parameters in these previous work were tuned to minimise the cost function and achieve optimal feedback gains and solve the Ricatti's equation.

Leonard & Graver (2001) designed the LQR for the ROGUE AUG. The LQR was designed for steady glides of 30° and 45° downward and upward. There was no significant tuning performed to optimise the controller parameters. Kan et al. (2009) designed LQR for the spatial motion model. The LQR was simulated for gliding angle of 30° downward. Then controller was also simulated for spiral motion where the AUG was initially glided at 30° downward and after 3000s it switched its motion to 30° upward. Wang et al. (2009) proposed LQR strategy for longitudinal plane that was able to track the pitching angle changing from 40° downward to 20° downward. For the hybrid-driven AUG, LQR strategy was firstly designed by Isa & Arshad (2012) for the USM hybrid-driven AUG and the results of this work showed that the LQR was able to track all states under control. Joo & Qu (2015) designed LQR to control the motion of a hybrid AUV. The LQR performance was tested for steady glide of 30° downward and upward. In the same year, Javaid et al. (2015) designed the LQR to control the longitudinal plane of the AUG. The LQR was simulated for two different wing designs which were tapered shape and rectangular shape to observe the behaviour of the glider motion with different shape of wing. A year after that, Tchillian et al (2016) also proposed the LQR for the longitudinal plane of an AUG. The LQR was designed based on the mathematical model similar to the one proposed by Leonard & Graver (2001).

As conclusion, the linear controllers provide good tracking performances. However, since the model is linearised about the equilibrium point, the performance of the controller is only effective in a small neighbourhood of the equilibrium.

2.4.2 Nonlinear Control Strategies

Most of the systems are nonlinear. The nonlinear control strategies offer a better option in handling the nonlinearities, uncertainties, disturbances and changes in parameters in which linear control strategy is unable to handle. There are various nonlinear controls have been implemented in AUVs and AUGs such as SMC, back-stepping control and adaptive control.

The SMC strategy is known for its robustness against perturbations such as parameter variations and external disturbances. Since the UVs are highly nonlinear with time variant dynamics, thus it is found in many research works in which the SMC technique was employed. The main drawback of the SMC is chattering phenomena that is induced by high frequency switching of the discontinuous control. However, many approaches can be used to reduce the chattering phenomena. The SMC application in AUVs can be found in Yoerger & Slotine (1985), Dougherty et al. (1988), Healey & Lienard (1993), Wang et al. (2002), Kim et al. (2015), Salgado-Jimenez & Jouvencel (2003), Khan et al (2012), Ruiz-duarte & Loukianov (2015), Zhou et al. (2015)Yoerger & Slotine (1985), Dougherty et al. 1988), Healey & Lienard (1993), Wang et al. (2002), Kim et al. (2015), Salgado-Jimenez & Jouvencel (2003), Khan et al. (2012), Ruiz-duarte & Loukianov (2015) and Zhou et al. (2015), and the application in AUGs can be found in Yang & Ma, (2010a, 2010b).

The first implementation of SMC in AUVs was found in 1985 by Yoerger & Slotine (1985). In this research, the boundary layer SMC control law was developed for the Experimental Autonomous Vehicle (EAVE) and this control law was only developed for the nonlinear model for the horizontal plane. Dougherty et al. (1988) proposed the conventional SMC that employed the signum function in discontinuous control. The controller was designed for hovering control of an AUV. Later, Healey & Lienard (1993) implemented SMC to control speed, heading and depth. The controller was designed based on decoupled subsystems which were speed, steering and diving subsystems. They employed the hyperbolic tangent smooth function to replace the signum function. Wang et al. (2002) employed the basic SMC which its signum function was employed in the discontinuous control for 5 DOF nonlinear system that controlled surge, sway, heave, pitching and yaw of a ZHISHUI-III AUV. In 2015, Kim et al. (2015) employed integral sliding mode control ISMC to reduce chattering. ISMC is also known as no reaching phase SMC until now since the algorithm ensures that the sliding begins at time, $t = 0$. In addition, Kim et al. (2015) had also developed controller control depth of Cyclops AUV.

Salgado-Jimenez & Jouvencel (2003) employed higher order sliding mode known as the twisting SMC and super twisting SMC (STSMC) for depth control of a TAIPAN AUV. The performances of both controllers were compared with PD controller. Khan et al. (2012) compared the performance of the conventional SMC, terminal SMC (TSMC) and STSMC. The controllers were designed to control the lateral dynamics of an AUV. Ruiz-duarte and Loukianov (2015) proposed the super twisting SMC to control depth of the AUV. The performance of the STSMC was compared to the nonlinear observer in term of robustness against external disturbance and parameter variations. Yang & Ma (2010a and 2010b) employed a method that combined the SMC with the reaching law which employed the method was called as rapid-smooth reaching law. The controller was developed to track the pitching angle and net buoyancy. The difference in the work between Yang & Ma (2010a) and Yang & Ma (2010b) is that in 2010a the control law was computed directly from the nonlinear dynamic of an AUG, whereas in 2010b the control law was derived from the inverse dynamic of the AUG. However, there was no comparison study with other controllers and no chattering is observed in sliding surfaces.

The backstepping is another technique used to control the motion of the AUVs and AUGs. The backstepping is known as a recursive systematic design methodology. It uses Lyapunov stability theorem to analyse the stability of the controller. The basic idea of backstepping is the design that breaks up into sequence of the sub-problems of the lower order of the system and then recursively uses the states as "virtual controls" to attain the intermediate control laws using the Lyapunov function. Several works based on backstepping control were reported in Caiti & Calabro (2010), Ferreira et al. (2011), Wei et al. (2015), Yu et al. (2013), Wu & Karkoub (2014), Harun & Zain (2016a, 2016b). Caiti & Calabro (2010), Ferreira et al. (2011), Wei et al. (2015), Yu et al. (2013), Wu & Karkoub (2014) Harun & Md Zain (2016a), Harun & Zain (2016b), Cervantes et al. (2016) and Rath et al. (2017).

Caiti & Calabro (2010) proposed the integral backstepping technique with fuzzy to improve the adaptation of the controller to hydrodynamics uncertainties and external disturbances. The controller was designed for the FOLAGA AUV. Ferreira et al (2011) proposed the backstepping control to the MARES AUV in the presence of thruster fault. Two control laws were derived to control the pitching angle and the depth of MARES AUV. Wei et al. (2015) researched on the backstepping control based on nonlinear disturbance observer (NDO) to control the depth of the AUV. The NDO is commonly used to estimate the disturbance. Yu et al (2013) employed the backstepping control based in integral SMC to control the AUV. The backstepping control law was derived for the nominal control part of the integral SMC and the boundary layer SMC was chosen for the nonlinear part.

Wu & Karkoub (2014) on the other hand suggested hierarchical backstepping to control the linear positions x, y, z and yaw angle of the AUV. The controller was tested for the system to function with presence of uncertainties. However, there was no performance comparison with other controllers made.

Within these recent years, Md Zain & Harun (2016a) proposed the standard backstepping and integral backstepping to control the linear position and attitude of X4-AUV. The controllers only tested for the nominal system. The results showed that the integral backstepping provided faster convergence, steady-state error was eliminated and transient was improved. In Harun & Md Zain (2016b, the backstepping with particle swam optimisation (PSO) was proposed to control the x-position and attitude of X4-AUV. The PSO was used to optimise the backstepping control gains. The performance of the proposed controller was compared to the performance of the back-stepping with manual tuning. However, the proposed controller was not tested in the presence of uncertainties.

In Cervantes et al (2016), the output based backstepping was proposed to control the linear position and yaw angle of the AUV. The algorithm of this work combined the backstepping like form and a robust exact differentiator. The simulation results proved that the proposed controller provided an acceptable performance. Recently Rath et al (2017) proposed the backstepping control for diving and steering planes of an AUV. The control laws for diving and steering planes were designed separately. However, the proposed controller was not tested in the system with the presence of uncertainties. For AUG, several works based on backstepping control were reported in (Burlion et al., , 2004; Caiti et al., 2012; Cao et al., 2015; Cao et al, 2016).

The hydrodynamic of the underwater vehicle contains the unknown disturbances and parameter uncertainties. Therefore, the adaptive controllers were utilised in various previous research works to control the vehicles and to estimate the parameters (Antonelli, 2007; Caiti & Calabro, 2010; Cristi & Healey, 1989; Guo et al., 1995; Sahu & Subudhi, 2014, Barbalata et al., 2015). (Antonelli et al., 2001; Antonelli, 2007; Caiti & Calabro, 2010; Cristi & Healey, 1989; Guo et al., 1995; Sahu & Subudhi, 2014; Barbalata et al., 2015).

Cristi & Healey (1989) proposed a model-based adaptive control to control the AUVs. The model of AUV was linearised in the equilibrium of the operating points. A recursive least square method and pole-placement were employed to develop the controller. Following this work, Guo et al. (1995) presented the adaptive control using neural network to control the heading of AUV. The controller was designed based on discrete model of AUV. The controller consisted of two stages. In stage one, the initial weight of neural network was firstly determined, and in stage two, the neural network was trained so that the cost function could be minimised and thus tracking error could be reduced.

In Antonelli et al. (2001), the adaptive control was designed to control the six degree of freedom (DOF) of ODIN ROV and AUV that combined SMC with an adaptive controller system parameter estimation. Later, Antonelli (2007) presented the adaptive control to control 6 DOFs of ODIN and AUV. However, in this work, the adaptive controller was a combination of PD with an adaptive/integral compensator to compensate the persistent dynamic effects such as the restoring forces and the ocean currents. In 2014, Sahu & Subudhi (2014) designed the adaptive controller to control the liner position and yaw angle of AUV. The adaptive control was combined with PD controller which was able to adapt the uncertainties in hydrodynamic parameters. One year later, Barbalata et al. (2015) proposed the adaptive control method to control the 4 DOFs of AUV. The adaptive control was used to determine the gain of the PD controller online basis through position/velocity error.

In general, the nonlinear control provides high robustness against nonlinear dynamics, uncertainties in hydrodynamic and environment disturbances. Many applications that are used nowadays usually combine two methods of control approach to enhance a single approach. However, the combination of backstepping and sliding mode control application in AUG is still open for implementation.

2.4.3 Intelligent Control Strategies

There are several categories of control algorithms fall under intelligent control. The NN and fuzzy logic controls (FLCs) are the most prominent controls employed for controlling the motion of the underwater vehicles. The advantage of intelligent control is its ability to adapt and robustness to the nature of highly nonlinear and dynamic environment of the underwater vehicles.