UNDERWATER GLIDER MODELLING AND ANALYSIS FOR VARIABLE CONTROL PARAMETERS

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UNDERWATER GLIDER MODELLING AND ANALYSIS FOR VARIABLE CONTROL PARAMETERS

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

x	-	Motion in the x-direction
y	-	Motion in the y-direction
z	-	Motion in the z-direction
u	-	Velocity in the x-direction
v	-	Velocity in the y-direction
w	-	Velocity in the z-direction
φ	-	Roll (rotation about the x-axis)
θ	-	Pitch (rotation about the y-axis)
ψ	-	Yaw (rotation about the z-axis)
η_1	-	position and orientation with respect to the earth-fixed reference frame
v_1	-	Vector $\dot{\eta}_1$ is corresponding time derivative
η_2	-	The vector Euler angle coordinates in the earth-fixed frame
v_2	-	Vector $\dot{\eta}_2$ is the corresponding time derivative
i, j, k	-	Unit vector in x,y,z directions
k	-	Axis lies in the direction of the gravity vector and is positive downwards
V	-	Speed in vertical plane
V_1	-	Speed related to x-direction
V_2	-	Speed related to y-direction
V_3	-	Speed related to z-direction

α	-	Angle of attack
β	-	Side slip angle
Ω	-	Angular velocity
m_v	-	Total mass of the vehicle
m_h	-	Distributed hull mass
m_w	-	Fix mass
m_b	-	Variable ballast mass
$\overline{m}$	-	Movable mass
r_w	-	Position vector from CB to m_w
r_b	-	Position vector from CB to m_b
r_p	-	Position of movable mass in body coordinates
m	-	Mass of displaced fluid
m_o	-	Excess mass, $m_o = m_v - m$
P	-	Total linear momentum in body coordinates
P_p	-	Linear momentum of $\overline{m}$ in inertial coordinates
P_{pi}	-	ith component of P_p
r_{pi}	-	ith component of r_p
g	-	gravitational force
D	-	Drag force
L	-	Lift force
M_{DL}	-	Viscous moment

LIST OF ABBREVIATION

A/D	-	Analogue to digital
AOSN	-	Autonomous Ocean Sampling Network
ARMAX	-	Autoregressive moving average exogenous
ARX	-	Auto-regression with extra inputs
AUV	-	Autonomous Underwater Vehicle
BJ	-	Box-Jenkins
CARX	-	Continuous-time ARX
CB	-	Centre of buoyancy
CFD	-	Computational Fluid Dynamics
CG	-	Centre of gravity
CPU	-	Central processing unit
D/A	-	Digital to analogue
DC	-	Direct Current
DOF	-	Degree of freedom
EOM	-	Simulation equation of motions
GOC	-	Glider Operation Centre
GPS	-	Global Positioning System
GUI	-	Graphic user interface
IMU	-	Inertial Measurement Unit
I/O	-	Input/output

LAR	-	Launch and Recovery
LTP	-	Linear Time-Periodic
MIMO	-	Multiple-input multiple-output
MSS	-	Multiple simultaneous specification
NACA	-	National Advisory Committee for Aeronautics
NAVOCEANO	-	Naval Oceanographic Office
NMS	-	Neuro-Musculo-Skeletal
OE	-	Output error
ONT	-	Office of Naval Technology
PE	-	Prediction error
PIC	-	Programmable interface controller
PWM	-	Pulse width modulation
RAM	-	Random-access memory
ROM	-	Read-only memory
SBC	-	Single board computer
S/H	-	Sample/holder
SIO	-	Scripps Institute of Oceanography
SNAME	-	Society of Naval Architects and Marine Engineer
USM	-	Universiti Sains Malaysia
WHOI	-	Woods Hole Oceanographic Institution
WRC	-	Webb Research Corporation

3D	-	Three-dimensional

PEMODELAN DAN ANALISA PARAMETER-PARAMETER KAWALAN BOLEH UBAH BAGI SISTEM PELUNCUR BAWAH PERMUKAAN AIR

ABSTRAK

Peluncur bawah permukaan air merupakan kenderaan bawah permukaan air tanpa pemandu dimana ia boleh meluncur dengan mengawal daya julangan serta kelakuan dengan menggunakan actuator yang terdapat di dalam kenderaan. Dengan hanya mengubah daya julangan kenderaan tersebut secara bersela, pergerakan kehadapan boleh terhasil. Bagi menerbitkan model secara matematik secara langsung daripada sistem boleh menjadi amat rumit kerana batasan masa semasa proses prototaip dilaksanakan. Tesis ini menerangkan pembangunan pelantar peluncur bawah permukaan air USM pada peringkat awal terdiri daripada rekabentuk prototaip dengan menggunakan perisian *Solidworks*^{TM}, penyahlakuan menggunakan perisian *Computational Fluid Dynamics* (CFD) serta tentang cara lain bagi pemodelan sistem dikenali sebagai sistem identifikasi dalam memperolehi model sistem peluncur bawah permukaan air. Kesesuaian parameter kawalan bagi sistem peluncur bawah permukaan air telah ditentukan dengan memilih kadar balast sebagai masukan, tiga aspek dinamik peluncur bawah permukaan air akan diperhatikan: daya julangan bersih, kedalaman kenderaan bawah permukaan air dan sudut anggul. Tiga model parameter yang berupaya menganggarkan sistem secara tepat dipilih dan ralat di antara keluaran yang diukur dan yang di anggarkan diterangkan bagi mendapat model peluncur bawah permukaan air USM secara optima.

UNDERWATER GLIDER MODELLING AND ANALYSIS FOR VARIABLE CONTROL PARAMETERS

ABSTRACT

Underwater glider is a type of autonomous underwater vehicle that can glide by controlling their buoyancy and attitude using internal actuators. By changing the vehicle's buoyancy intermittently, forward motion can be achieved. Deriving the mathematical model directly from the system can be too complicated due to time constraints in prototyping development processes. This thesis presents the early development of the USM underwater glider platform consist of prototype development involves vehicle concept design using Solidworks^{TM}, vehicle simulations by Computational Fluid Dynamics (CFD) and alternative way of modelling known as system identification in order to obtain the underwater glider system model. The appropriate control parameters for underwater glider control were determined by selecting the ballast rate as the input. Three aspects of the dynamics of a glider will be observed, i.e. net buoyancy, depth of the glider and pitching angle. The best three parametric models that are able to estimate the system correctly are chosen, and the fit between measured and estimated outputs is presented in order to get an optimal underwater glider vehicle model for USM underwater glider platform.

CHAPTER 1

INTRODUCTION

1.0 Motivation for Study

The motivation for this work comes from the desire to understand the underwater gliders moves through the water without any moving parts or driving mechanism physically. Underwater gliders propelled completely using internal mechanisms such as variable ballast system and movable internal mass. Malaysia is rich with marine resources and need to be explored using this new underwater platform. There is none of underwater gliders operates in this region and it will contribute to a new method in exploring our resources. Therefore a working underwater glider prototype for testing purposes is needed for system optimization. Research has to be done to familiarize the control system, power requirement and variable mass system in order to improve current control system to bio-inspired system for future works. This unique underwater platform thrusting in the water mimicking the ocean mammals without external thrusters is the most suitable platform for underwater research. Lastly is to contribute in embarkation on underwater gliders platform development that can be used in tropical water.

1.1 Underwater Glider System

Underwater gliders are a new type of underwater robotic platform that glides through the water. Like the sailplanes (airborne) concept, it glides on thermal column to increase the lift while low in drag design. Using the wings with low in drag and laminar flow airfoil it can glide without using the engines and can remain airborne for hours.

These wings design and concept are implemented on underwater gliders. With wings, underwater gliders glide through water column by adjusting the buoyancy thus changing the altitude or depth. The advancement of satellite provides the navigation and communication gateway for any underwater robotic platforms that are changing the way the ocean is observed (Davis et al., 2002). Underwater gliders can improve our understanding in marine and other environmental issues, protect the ocean resources of the earth from pollution, and efficiently utilize them for human welfare.

The platforms can be observed autonomously far away from the control station. Data transfer and mission status can be updated through satellite link so it can be monitored periodically. Underwater gliders can be fitted with the state of the art sensors technology that can give a view of the interior ocean with much higher spatial and temporal resolution than is possible with conventional shipboard and moored instrument (Leonard et al., 2007). Oceans represented 99% of the earth's ecology that can support life and many oceanographic phenomena still need to be studied (Yuh, 2000; Woithe et al., 2008). Underwater gliders are becoming increasingly popular as observational platforms in operational oceanography as they allow for persistent sampling in weeks, months duration and are capable of resolving subtle changes in the marine environment over desire temporal and spatial scales (Mahoney et al., 2009).

Figure 1.1 Underwater Glider (Davis et al., 2002).

1.2 Underwater Gliders Characteristics

Underwater gliders unique design is the buoyancy changing mechanism to create forward glide motion without using thrusters or propellers. Variable ballast system contributes the changing of the underwater gliders buoyancy thus making the gliders to glide downwards and upwards straight glides in saw tooth pattern, turning and gliding in a vertical spiral. Underwater gliders can be programmed to hold their position by gliding against the current, adjusting themselves neutrally buoyant and drift along the current or rest on the bottom. Without using the propellers as the main propulsion system, gliders are capable for long range and high endurance deployments. The shallowest points on the saw tooth pattern are at the surface where satellite communication are carried or via radio frequency link. With long endurance covers thousands of kilometers, duration, control and global data relay through satellite, many new missions are anticipated.

1.3 Underwater Glider Applications

Underwater gliders are suitable in multi applications such as physical, chemical and biological oceanography. Current available sensors that can be integrated with the underwater gliders are conductivity, temperature, depth average currents, surface current, chlorophyll fluorescence, apparent and inherent optical properties. Climate changes documentation can be done using underwater glider platform for temperature monitoring on water column (Schofield et al., 2008). It is recommended to use unmanned robotic platform to classify the dangerous and hostile environment for humans especially in coastal areas. Harmful alga blooms can cause harm via toxin production, or by their accumulated biomass. Such blooms can cause severe illness and potential death to human as well as to fish, birds and mammals (Smith et al., 2009). Underwater gliders platform are suitable to these kind of missions based on their movement underwater by gliding through water columns.

Others applications includes as the underwater communications gateways or navigation aids to other underwater platforms or ships. Communication gateways from space to underwater and vice versa were established using multiple underwater glider platforms as mobile network nodes while underwater modem and surface station as a fixed network (Bachmayer et al., 2004). Due to its unique motion and low in acoustic noise, underwater gliders suitable in military applications in mines counter measures (airborne and maritime), tactical, oceanography and anti submarine warfare for The Naval Oceanographic Office (NAVOCEANO) and Glider Operation Centre (GOC) U.S (Mahoney et al., 2009). Without propellers, these platforms can be very silent and efficient in doing reconnaissance and waiting on the bottom according to the mission.

This is an attractive feature for multi applications because quieter vehicles are suitable in marine environment due to lower acoustics noise levels.

1.4 Objective of Research

The main aim of this research is to determine an optimal vehicle model for USM's underwater glider platform. In order to achieve the target, three main objectives are carried out, as follows:

- To design and develop of an underwater glider prototype.
- To determine the appropriate control parameters for underwater glider control.
- To implement a system identification method for underwater glider modelling process.
- To determine the optimal underwater glider vehicle model and validation for USM underwater glider platform.

1.5 Scope of Research

This research will focus on the design and development of an underwater glider prototype, simulation aspect of underwater glider modelling and analysis for variable control parameter. Due to the time constraints, budget and testing facilities, this research will not cover the proofs of concept on using real underwater glider platform.

1.5 Organization of Thesis

Chapter 1 presents the overview information about Underwater Gliders technology characteristics, research objective, and motivation for study effort.

Chapter 2 presents the history of underwater gliders development and current underwater glider design. Introduction of system identification process were also presented.

Chapter 3 presents the methodology employed in this research study starting with design and development of USM underwater glider prototype and modelling based on equation of motions. System identification process and simulation equation of motion for underwater glider modelling process are also presented.

Chapter 4 outlines the simulation results obtained from the study. This chapter report on the results obtained during the test explained in chapter three and four respectively.

Finally, Chapter 5 concludes the work in this research. This chapter also summarizes the limitations of the system and several suggestions for future works.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Underwater gliders are the new kind of underwater sensors platform that gave a different perspective in oceanography sampling process. Data such as temperature, salinity/conductivity, currents, and depth are the very important parameters to understanding the behaviour of our ocean and its dynamics. Temperature and salinity are varied significantly in vertical variation compare to the horizontal variation. Due to this dynamics changes, oceanography studies often require a series of temperature, salinity and current profiles by depth in many locations.

Underwater sampling requires on site measurement due to physical of seawater and requires dedicated and workable sensors during mission. The ocean and fresh water absorbs light, radiation and thermal energy in a relative short distance. For example electromagnetic wave attenuates exponentially during underwater penetration while sound wave propagates well inside the water. This acoustic energy could travel very far away depending on the frequency of the signal and that is the main reason for using these phenomena in underwater telecommunication and underwater navigation. The variation of the pressure or depth, temperature and salinity will affect the acoustic propagation wave through underwater. The optimum of acoustic propagation determines by these parameters whether in direct path or refracted upward or down depending on the thermal layer conditions (Frieden and Bender, 1985).

The variation of the temperature and conductivity as a function of depth together with the biological sensor indicates a major impact on environment, from marine ecosystem to climate change (Leonard et al., 2007). The sampling involve not only at the surface of oceans but most important underwater environment as well. Acquiring data at depth requires fixed mooring, floats, drifter, or ship dragging equipment and sensors will give difficulties of communicating through the ocean with sensor under deployment and need to be used in large scale to cover wide range of area.

Current trend of oceanography sampling technology must be able to communicate using variety of communication network such high frequency radio through the atmosphere and satellite link throughout the world coverage via command centre located far away. Underwater gliders can be used as sensor networks by collective motions among them using the current communication networks such as GPS, satellite modem and high frequency radio transceivers. Underwater gliders can overcome all the difficulties facing oceanographer by offering new kind of sensors platform in understanding the oceans in new perspective of sciences.

2.1 History of Underwater Glider Concept and Development

The underwater glider concept and its applications originated in the 1980's with Doug Webb and Henry Stommel in Woods Hole Oceanographic Institution (WHOI) and Falmouth, MA. Stommel was a famous oceanographer and the creator of the modern field of dynamical oceanography while Webb is known for, among many other things, his innovative work in ocean engineering and instrumentation for oceanography, as well as his extensive work on drifters for oceanographic sampling (Wunsch, 2005; Graver, 2005).

Webb's idea on developing oceanography floats and buoyancy system creates a new concept of gliding vehicles known as underwater glider. Starting with Bobber floats design that's move up and down in the water autonomously combining with thermal power buoyancy engine to reduce power consumption (Webb et al., 2001). This thermal engine concept make use of ocean's thermal layer differences in temperature with depth to power up the float's movement between the warm surface water and the colder depth. This would extend the number of ballasting system and giving the vehicle more endurance and that is where the first glider prototype called Slocum was introduced. Slocum name came from New Englander Joshua Slocum who sailed around the world alone on 1895 (Graver 2005).

The first prototype testing on Slocum electric was perform 29 dive up to 20 meter depth on January 1991 at Walkulla Springs in Florida followed by lake testing at Lake Seneca, New York November 1991 and thermal buoyancy engine floats. Testing was conducted in Lake Seneca due to sufficient depth and temperature gradient for the thermal buoyancy engine (Simonetti, 1992) under Office of Naval Technology awarded grant. The Slocum electric prototype tested at that time had the main characteristics in today's underwater gliders, with an electric pump, fixed wings and tail, and a moving internal mass to control pitch and roll (Rudnick et al., 2004). Henry Stommel passed away on 17 January 1992.

The successful of Slocum field trials during early 1990 bring up active research on underwater gliders development programs. Office of Naval Technology has giving increased amount of funding in underwater glider concept development and led to three programs to design and develop oceanographic gliders:

- The Slocum Glider at Webb Research Corporation (WRC).
- Seaglider at University of Washington.
- Spray at Scripps Institute of Oceanography (SIO).

Within ten years these group have developed and deployed them in large scale oceanography projects. Slocum electric gliders produced by WRC was the first prototype to be commercialized and being sold to WHOI Glider Lab. Table 2.1 shows some development and achievements of oceanographic gliders since it first prototype.

Table 2.1 : Underwater gliders development history

Year	**Achievements**
1989	"The Slocum Mission" appear in *Oceanography* (Stommel, 1989).
1990	Office of Naval Technology (ONT) awards WRC contract for Slocum prototype (Graver, 2005).
1991	Test of Slocum prototype and thermal engine at Wakulla Springs and Lake Seneca (Stommel, 1989).
1992	First development of ALBAC glider at University of Tokyo (Kawaguchi et al., 1993).
1993	Autonomous Oceanography Sampling Networks paper appears in *Oceanography* (Graver, 2005).
1999	Slocum gliders tested at LEO-15 Observatory, New Jersey. Slocum gliders

	continue to be used there for ocean sampling till 2005.
1999	Autonomous Ocean Sampling Network (AOSN) conducted in Monterey Bay, California. Spray prototype glider also been deployed for 11 days and three Seagliders were also been deployed.
2000	Spray, Slocum and Seaglider have completed 10 day missions.
2001	Seaglider makes 280 km section from San Diego.
2002	Seaglider travels over 1000 km off Washington Coast.
2003	Development of three Slocum Gliders in Bahamas by WHOI. Trials of thermal Slocum prototype conducted by WRC on same cruise. (January)
2003	SPAWAR and Canadian Navy conducted tests in Gulf of Mexico of three Slocum Electric gliders equipped with acoustic modems. (February)
2003	AOSN II conducted in Monterey Bay. Twelve Slocum and five Spray gliders are deployed. (August)
2004	Spray glider is the first Autonomous Underwater Vehicle (AUV) to cross the Gulf Stream about 960 km.
2008	Slocum, Seaglider and Spray were widely used in European countries and Australia.
2010	Slocum glider makes a history to cross Atlantic Ocean from New Jersey, USA to Spain (Shapiro, 2010).

2.2 Current Underwater Glider Designs

All the current gliders technology design grew from the initial Slocum glider concept and since then multiple gliders such as Slocum (Figure 2.1), Spray (Figure 2.2) and Seaglider (Figure 2.3) have been manufactured and developed in large scale oceanography projects. Some important features include low operational and capital cost, high range and endurance due to minimal power consumption, durability, low noise and vibration and autonomous operation (Eriksen et al., 2001; Herman et al., 2001; Davis et al., 2001; Webb et al., 2001).

These three gliders have a similar dimensions, fixed wings and tail and used internal mass actuators to control pitching and rolling conditions (Rudnick et al., 2004). All use electrically driven buoyancy systems and internal moving mass except for Slocum thermal buoyancy engine. Spray and Seaglider use ballast system derived from ALACE float, which use a Ludec pump to move oil between an internal reservoir and an external bladder. These pumps are more efficient at deeper depth in term of energy usage because most of the glider energy goes to pumping work. Section 2.3 will describe the features of existing gliders.

Figure 2.1 Slocum (Smith et al., 2009).

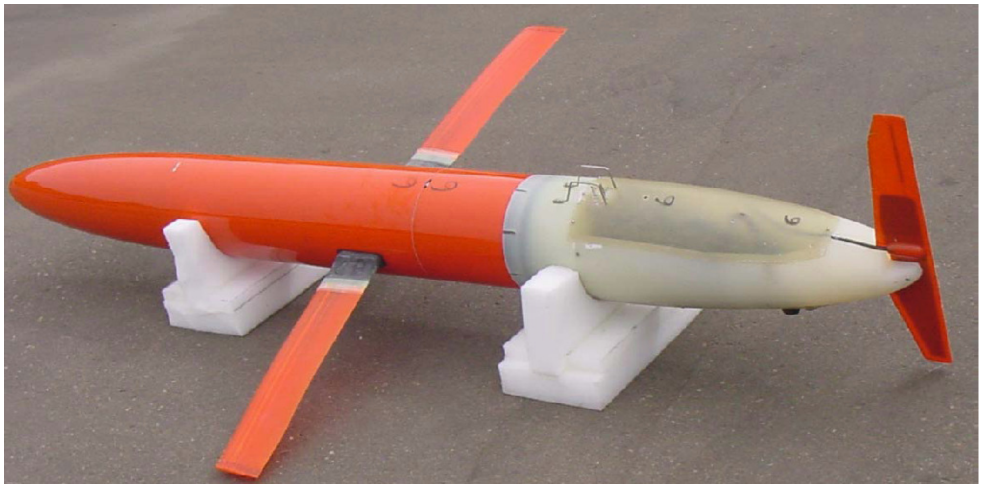

Figure 2.2 Spray (Sherman et al., 2001).

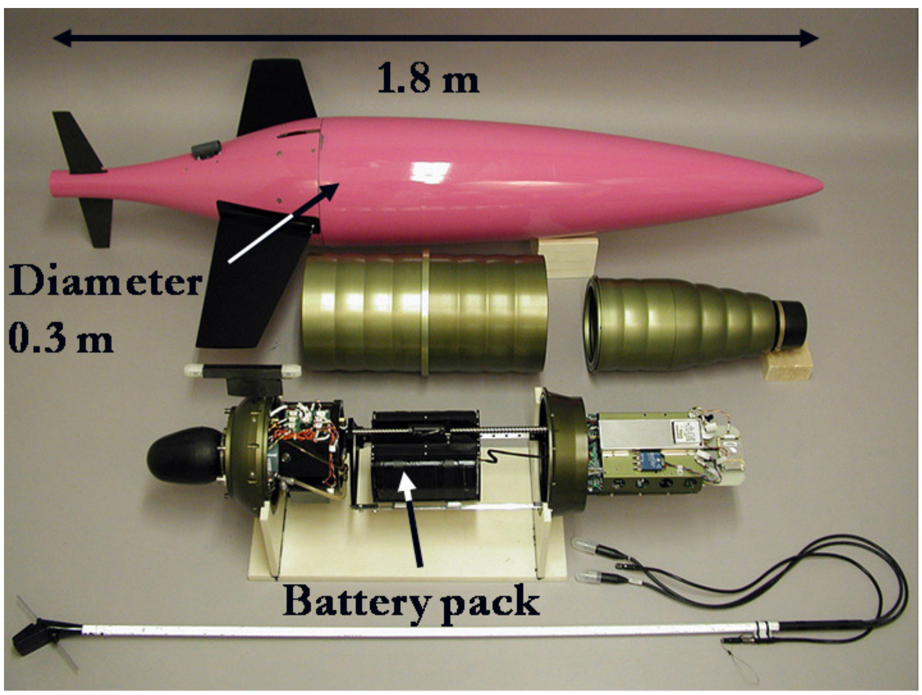

Figure 2.3 Seaglider (Eriksen et al., 2001).

2.3 Features of Existing Gliders

This section describes some existing underwater gliders designs and features which will become as guidance on developing the underwater glider platform. The most important features in the gliders platform are the buoyancy engine and movable mass subsystem. With these different features and platforms, it is hope to get some idea in developing this research work.

2.3.1 Slocum

Slocum glider came with two different buoyancy power engines; those were Slocum Electric and thermally power Slocum. Slocum Electric can be operated until 200 m of depth while Slocum with thermally power principle can be operated until 1500 m of depth. The Electric Slocum is 1.8 m long and glides to depth 200 m at speeds around 0.5 m/s and 52 kg of total mass. The tail is 0.3 m long and uses syringe type ballast pump with 500 cc volume capacity located behind the nose of the glider. Pitch is controlled by moving a battery pack while roll is trimmed statically. Slocum has fixed wings and vertical tail with rudder. The tail section is equipped with antenna for GPS and communication.

2.3.2 Spray

The spray glider developed at SIO, is two meters long and has a mass of 50 kg. Spray was named after Joshua Slocum's ship. Spray operating speed 20-30 cm/s and ranges up to 6000 km. Spray has a cylindrical pressure hull with two wings and a vertical tail. A flooded fairing forms the rear of the hull and houses the external oil-filled bladder for the ballast system. The ballast pump system is derived from ALACE floats pump and uses an improved design including an added priming pump and a greater compression ratio. Spray using two internal moving masses for pitch and roll control. The roll actuator is a battery pack located in the nose of the vehicle and rotating in 360degrees. The pitch actuator is a battery packs moved by a rack and pin actuation system driven by DC motors. The battery packs has range of travel of 10 cm and will be able to move the center of gravity (CG) up to 17 mm. Spray's antenna is located inside one of the wings so the vehicle need to roll on its side to extend this wing above the surface for GPS and communication.

2.3.3 Seaglider

Seaglider was developed by The University of Washington Applied Physics Lab for extended oceanographic sampling missions. It has a range roughly 6000 km or 900 dives to 1000 m depth. It has 52 kg of mass and its hull is made up of an internal pressure hull and an external fairing. The fairing is 1.8 long with 30 cm maximum diameter and is free flooding. Seaglider is capable to dive as deep as 1500 m and pump efficiency will increase proportional to depth. The isopycnal hull design will reduce the ballast pumping requirements by matching the compressibility of the sea water. This feature extends vehicle range by as much as fifty percent over a conventional stiff hull (Eriksen et al., 2001).

The Seaglider external fairings are made by carbon fiber material and its shape is derived from a low drag laminar flow shape to reduce pressure drag by developing a favourable pressure gradient at the rear of vehicle. Seaglider mounts the GPS and wireless modem antennas at the end of its antenna mast. The antennas are water proofed by potting booth antennas into a mold along with the graphite tube. Pitch and roll are controlled by moving and internal battery pack same principle with Slocum and Spray.

2.3.4 ALBAC

The ALBAC glider was developed at the Underwater Robotics and Applications (URA) Laboratory, University of Tokyo in 1992. This design is notable because it is a shuttle type glider designed to conduct dives from a ship and does not have buoyancy control system. ALBAC is driven by a drop weight which it carries on one downward glide and then released the weight to ascend back to surface by conducting a single trip to depth between deployment and retrieval. ALBAC has fixed wings and vertical and horizontal tail. It is 1.4 m long and 45 kg of mass. It can dive to 300 m depths at speed of one to two knots (0.5 to 1.0 m/s). ALBAC has horizontal tail fins which can change angle at inflection from downwards to upwards gliding, a feature that are not presented in other gliders. It moves a battery pack internally to control pitch and yaw in the same manner as Seaglider.

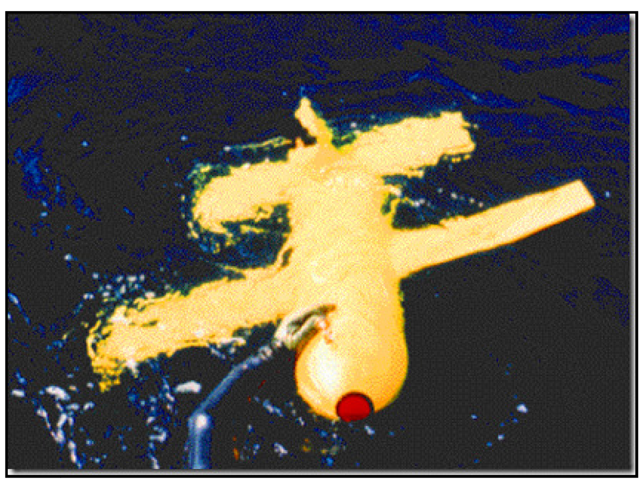

Figure 2.4 ALBAC (Kawaguchi et al., 1995).

2.3.5 ALEX

ALEX underwater glider was developed at Osaka Prefecture University, Department of Marine System Engineering. The design was to develop an underwater glider with independently controllable main wings for use of oceanographic survey, wide range monitoring of marine environment by using lots of swarming intelligent underwater glider (Arima et al., 2008). The different between other gliders with ALEX was the high performance of motion due to controllable main wings. The main wings design composed of servo motors with angle of incidence from negative 10 degrees to positive 10 degrees. The total length is about 0.83 m and 0.085 m of diameter. The ballast system is equipped with vent/blow valve to control the N_2 compressed gas cylinder for surfacing procedure. The body is made from acrylic cylinder with 2 mm thick and the total mass is 4.39 kg. There is 1.2 kg movable balance weight made of brass for pitch control and payload space about 300 centimeter cube for electronics and sensors load. It also equipped with 6 channel radio control system for human control during surfacing.

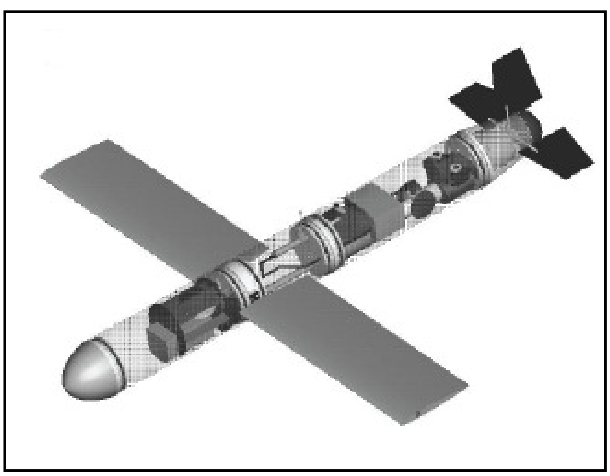

Figure 2.5 ALEX (Arima et al., 2008).

Some important features of existing glider designs as guidance for the carried out research in this thesis are:

- Ballast system to control buoyancy.
- Moving internal masses to control attitude using one mass.
- Symmetrical designs with fixed wing for gliding both up and down.
- Fixed rudder for vehicle stabilization.
- Use of low drag hull shapes using Computational Fluid Dynamics (CFD) analysis.
- Shallow water application not more than 50 meter in depths.

2.4 System Identification and Modelling

System Identification is the experiment approach to process modelling. It has been a fundamental part of obtaining knowledge of any physical system that is observed and to determine it in adequate detail in analysis and parameter estimation. System identification is implicitly in all possible areas such as biology, medicine, chemical process, economics, geology, materials, civil and mechanical engineering, automobiles, flight vehicles and etc. The real process in many systems is too complex and the exact internal behavior is unknown such as mathematical model. It is possible to postulate a very comprehensive model that includes all the conceivable influences or based on theoretical formulations but that does not mean a good system representation (Ljung, 1999; Jategaonkar, 2006). Identification is methodological principles which minimize the redundancies and inconsistencies in the model into specified tolerance which has the minimum number of parameters. This is necessary due to simpler models are easier to interpret and for practical reasons of testing, estimation and cross-validation.

In order to understand the underwater glider system dynamics and its related properties, an accurate mathematical model that represents the system is highly needed. Thus, it is desirable to derive the equations of motion of the prescribed vehicles and take advantage of the vehicle's geometrical properties. There are few good references that discussed on underwater vehicle modelling. See for examples in (Fossen, 1994; Prestero, 2001; Fossen, 2002; Graver, 2005; Petrich, 2009). Here, the use of Euler method, Runge-Kutta method, Newtonion method and Lagrangian method are employed to derive a six degree of freedom of equations of motion. Take for example the underwater glider modelling by Graver as a reference (Leonard and Graver 2001; Graver 2005). The equation of motion for underwater gliders is derived from the first principle to include the major design elements including buoyancy control, wings and external control surfaces and nonlinear coupling between the glider and internal mass actuators.

System identification methodology for a linear time-periodic (LTP) and linear time-invariant has been demonstrated by (Shin et al., 2005). A practical system identification method has been developed to estimate such multi component harmonic transfer functions for helicopter rotor in forward flight. Forward flight conditions are selected since it generally induces helicopter vibration. Active rotor system is experimentally identified for its vibration control design. The result enable such prediction since transfer function results are obtain over a range of frequencies of interest and it also enables improvement of control law in case instability is predicted.

System identification method was used to identify the neural control mechanisms that are involved in regulating the movement of the cat's hind legs during locomotion. Data for system identification and analysis were obtained using a three-dimensional (3D) forward dynamics computer simulation model which incorporated two hind limbs of a walking cat which each actuated by eight simulated muscles as presented by Harischandra and Ekeberg (2008). Simulation of neuro-musculo-skeletal (NMS) elements of the cat hind legs can be used to identify open-loop linear transfer functions from limb muscle activations to joint angles throughout the whole step cycle. A novel method to identify the musculo-skeletal system that is isolated from neural control and sensory feedback mechanisms while the system in locomotion mode is introduced using system identification method.

Multivariable system identification was investigated by Yau et al., (2007) to design a controller for the longitudinal channel of a Boeing 747 transport. Multivariable identification is performed by collecting input-output data samples using numerical simulation of the system represented by the mathematical model aircraft. The discrete transfer function matrixes of the system are identified using prediction error (PE) method with auto-regression with extra inputs (ARX) model. The identified plants are validated by using the model validation in which the worst-case v-gap is compared with the maximum value of the generalized stability margin. Integrated pitch/speed multiple simultaneous specifications (MSS) controller is designed based on the identified model of the Boeing 747 transport aircraft. Finally the controllers are validated by simulation using the true plant transfer functions.

Regarding to Mohd-Mokhtar and Wang (2005) system identification method was implemented to identify the multiple-input multiple-output (MIMO) complex system using frequency response data. Magnetic bearing system is selected for this complex identification process due to nonlinear, unstable and multivariable system. MIMO continuous time transfer function for a test-stand magnetic bearing apparatus is identified using continuous time subspace identification using frequency response data with an adoption of Laguerre network and an instrumental variable method.

Research work done by Larsson et al., (2007) to identify the irregularly sample data using system identification continuous-time ARX (CARX) models and proven to be fast compared to conventional method. This is suitable for data irregularly due to fast sampling process for higher quality data. Results are given for how the different operator should be chosen in order to obtain consistent parameter estimates. CARX model can be very useful for data that are sampled irregularly and the control design is made in continuous time. System identification method can be implemented for irregularly sampled data so it can be estimated.

System identification is the process of determining adequate mathematical model, usually containing differential equations, with unknown parameters which have to be determined indirectly from measured data (Harischandra and Ekeberg, 2008; Ljung, 1999; Jategoankar, 2006; Yau et al., 2007). The process includes not only model postulating and determining parameters but also performing suitable experiments and gathering system inputs and responses. These unknown parameters will give the model response that matches adequately the measured system response. In real process the perfect fit may not be possible due to type of model being selected and experiments process. So parameter estimation needs to be followed by step called model validation to assess model fidelity. If the identified model does not meet the requirements, the model structure has to be changed and the whole processes need to be repeated.

2.6 Summary

In this chapter, underwater glider history, development and design have been reviewed. Underwater glider platform can provide a new way of underwater survey and sampling with higher autonomy and reduce amount of energy needed for oceanography survey. The development of underwater glider especially to derive a model directly from physical law can be too complicated due to time constraint in achieving goal for prototyping development process. Therefore, other alternative that is easier, time save and less complicated should be considered. System identification procedure will construct the mathematical model of the system using the input and output data . System identification and modelling will be discussed in Chapter Three while the development of USM underwater glider will be discussed in Chapter Four.

CHAPTER 3

METHODOLOGY

3.0 Introduction

This chapter deals with the methodology and research implementation. The methodology has been divided into three phases namely design and development, underwater glider modelling and system identification of underwater glider. The USM underwater glider prototype was developed in order to investigate the system identification process for process modelling. The development was done by designing the prototype using Solidworks™ design software followed by system implementation of USM underwater glider prototype via Computational Fluid Dynamics (CFD) for hydrodynamic analysis. Modelling of underwater glider was done by implementing the kinematics of the underwater vehicle followed by the underwater glider mass distribution. Motion in the vertical plane is adopted to simplify the mass distribution on the vehicle. Identification process for USM underwater glider prototype is discussed. Model of Linear Time-Invariant system are selected for process modelling via various models. Figure 3.1 represents all the activities contain in each phase.

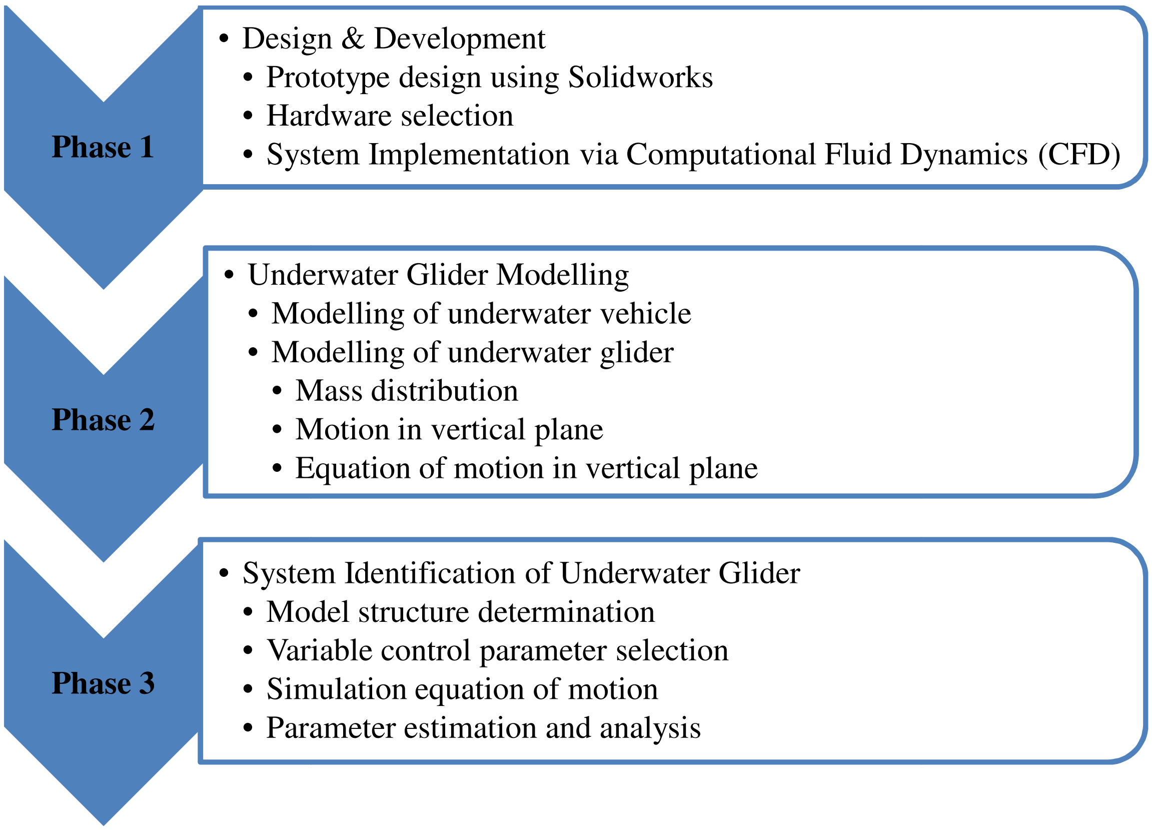

Figure 3.1 Research phases and activities

3.1 Prototype Design and Development

Underwater glider design and development approach can be different from one another due to user requirements, amount of funding and man power involved. It also relies on whether some user needs to utilize high sophisticated sensory system and amount of prototype endurance in term of duration of mission and maximum gliding depth. Some of the design examples can be seen as in (Graver, 2005; Ross, 2006; Arima et al., 2008; Alvarez et al., 2009). Early development of prototypes design using simulation is useful to investigate the vehicle behaviour. CFD analysis is useful for hydrodynamic forces approximation and to study the prototype performance in advanced (Seo et al., 2008; Seo et al., 2009). Study is conducted on the prototype shape