Design and Development of Underwater Glider

by

Erizeanne Binti Anthony Aga

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons.)
(Mechanical Engineering)

SEPTEMBER 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Design and Development of Underwater Glider

by

Erizeanne Binti Anthony Aga

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons.)
(MECHANICAL ENGINEERING)

Approved by,

____

Ir. KAMARUDIN BIN SHEHABUDDEEN
Project supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

ERIZEANNE BINTI ANTHONY AGA

Abstract

Underwater glider is a type of the autonomous underwater vehicles (AUV) that are commonly used for oceanographic data collection. It manoeuvres in the water by changing its buoyancy and adjusting its wings to enable horizontal propulsion. Thanks to its lower production cost and its capability for long-range, extended-duration deployments, underwater glider gained more interest from the oceanographic researchers.

This project aims to focus on the design and development project of underwater glider which has been motivated by several elements. This includes the interest in improving the functionality of underwater glider to carry a certain amount of payload, especially for subsea intervention. This application of underwater gliders is vital and understanding of their dynamics is crucial before a design can be produced. Therefore, this project shall focus on the governing equations underlying the principle of underwater glider to provide a database of model parameter values for various sizes of underwater glider dependent to the amount of payloads they carry.

To expand the database parameters for the design and development of underwater glider, few aspects need to be considered and together with some hydrodynamics assumptions, governing equations relating to the design of underwater glider was programmed into Microsoft Excel spread sheets. The outputs obtained from the spread sheet were compared to the existing underwater glider's parameters. The existing underwater glider's parameters were obtained from Marine Technology Society Journal. It is shown that the results are comparable with percentage error less than 20%.

ACKNOWLEDGEMENT

I would like to thank Universiti Teknologi PETRONAS (UTP) for providing necessary facilities and financial support for me to carry out my Final Year Project.

I would also like to express deep gratitude and appreciation to supervisor, Ir Kamarudin bin Shehabuddeen for his assistance and guidance throughout this two semesters. I am deeply thankful for his steady encouragement, insight and support throughout the course of this final year project. I would also like to thank him for his generous time in spite of his busy schedule.

Besides, I also feel grateful to my colleagues for their helpful advices and guidance in completing this report. I feel grateful to them for their insight and numerous helpful discussions regarding the early formulations of the methodology used for this final year project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

CHAPTER 1

INTRODUCTION

1.1 Background of project

Over the years, various strategies and techniques has been carried out for ocean explorations. Besides, many new inventions and devices are developed for the same purposes which include monitoring, maintenance and construction operations on or beneath the sea floor. These tasks can be done by divers in a relatively shallow depth. However, aids from robotic devices are needed in dealing the tasks at a greater depth.

Subsequent to that, autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) gained a significant interest from the ocean researchers. These two types of vehicles are normally used for navigation purposes such as exchanging information and data with the ship or station as well as acquiring information of oceans and life-forms [1].

This current study brings about new ideas to be implemented to the design and development of underwater glider, a type of AUV that is commonly used for oceanographic data collection. It does not have external propulsion system equipped on it and it manoeuvres in the water by using its control flaps and its vertical movements is governs by its weight and buoyancy. It is attractive because of its low cost and its capability in performing ocean sampling missions with significantly long range and duration deployments which could extend from hours to weeks or months and to thousands of kilometres of range.

This project is focusing on the design and development of underwater glider, especially the governing equations corresponding to the hydrodynamic analysis of underwater glider's movement in water while carrying a payload. This glider will be designed by considering the buoyancy concept to enable the glider become float and determining the dimension of its wings based on the developed governing equations obtained from previous research studies as well as the hydrodynamic assumptions.

By relating the application of underwater glider in the current engineering, we shall see the significance in improving its functionality to fit the current issue. For instance, underwater glider shall be used where sub-sea intervention is required especially when there is an immediate need to transport equipment for subsea operations and maintenance purposes. A delayed intervention would result in substantial environmental impact such as the Deepwater Horizon incident that occurred at the Gulf of Mexico. By ensuring that supplies are readily and quickly available, this would lessen the time to intervention by minimising the ROV waiting time. This will consequently lead to the improvement in transportation of supply and tools through rapid delivery to subsea and thus, operational cost can be reduced.

1.2 Objective of project

This project aims to study on the dynamics of underwater glider to better analyse the concept and principles underlying the design of underwater gliders that is carrying a payload. From here, we shall look into the parameters related to the gliders such as the buoyancy concept and hydrodynamics forces subjected to it as it travel underwater so that mathematical equations can be developed to guide the design of an underwater glider and to provide a database of model parameter values for various sizes of underwater glider dependent to the amount of payloads they carry.

1.3 Scope of project

The scope of work, tasks and study involved are related to the principles underlying the design and development of underwater glider. These include mass of underwater glider with payload that has effect on the buoyancy of the whole system, optimum wing area to enable the underwater glider to manoeuvre smoothly in water, study of how the horizontal and vertical stabilizers work and last but not least the hydrodynamic forces acted on the underwater glider such as the lift and drag force. All these will eventually aid in the overall outcome of this project which is to develop mathematical equations related to the design of an underwater glider and to provide a database of model parameter values for various sizes of underwater glider dependent to the amount of payloads they carry.

1.4 Problem Statement

The environment in the ocean is hard to predict due to its inconsistent current speed and tidal waters. Besides, maintenance of equipment installed in the ocean need to be regularly done in order to avoid negative substantial environment impact as what had happened over the Deepwater Horizon rig 5,000 feet at the bottom of the Gulf of Mexico. Due to the lengthy time in supplies/equipment delivery, the ROV waited about a day to carry out its task. Consequent to this, it gives worse impact to the environment. It is known that over 70% of the earth is covered by water, so we need vehicles that are able to move on the ocean without risking people's life. Thus, in order to solve the problem, the study of design and development of underwater glider is done. Aligned to this aim, dynamic analysis of the gliders will be looked into as to produce a database that enable designer to build an underwater glider that could carry a certain amount of payload. This task is challenging as underwater glider dynamics are complex and this study is still new.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews some of the previous studies and research papers on underwater glider that have been designed and developed. Underwater glider is an autonomous underwater vehicle that has the capability to manoeuvre under water with low power consumption by controlling its buoyancy and converting vertical motion to horizontal with the help of fix wings and the internal actuator that changes the position of centre of gravity. Thanks to its special characteristics, underwater gliders are able to travel under water at a significant range up to thousands of kilometres and duration from weeks to months. Based on 'Underwater Acoustic Glider', the authors mentioned other advantages of the underwater glider which include: 1) traveling profile samples horizontally and vertically; 2) regular surfacing for GPS navigation and two-way communications; 3) quiet with minimal impact in the environment being sensed [2].

The concept of the underwater gliders was proposed initially by Henry Stommel in 1989 [3]. Three ocean going gliders have been developed since 1995, including the SLOCUM glider [4], the Spray glider [5] and the Seaglider [6]. As stated in 'Underwater Glider Model Parameter Identification', the authors identified that all the mentioned gliders share the similar characteristics in terms of size, weight and configuration due to its similar purposes [7].

As time goes and as new innovation came into mind, this underwater glider is developing continuously. In 2006, Liberdade/XRay which is said to be the world's largest glider had been developed. It uses a blended wing body hull form to achieve hydrodynamic efficiency and space for energy storage and payload [8]. As a matter of fact, besides for oceanographic measurement, underwater gliders can also be used for industrial application especially for subsea intervention purpose that will enable underwater gliders to carry payload. Having said so, the main aim of this project is to develop some governing equations that shall be used to design future underwater glider that can serve that purpose.

Thus, it is essential to have strong background knowledge and fundamental concepts and theory about the physical laws governing the underwater vehicle in its environment. These include factors such as stability, hydrodynamic forces and buoyancy concept. Brief design concepts of different types of underwater glider; specifically Seaglider (Eriksen et al.,2001) built at the University of Washington, Slocum Battery manufactured by Webb Research Corp and Spray (Sherman et al., 2001) built at Scripps Institution of Oceanography are discussed here to better understand how they function.

Seaglider and Spray used reciprocating (multi-stroke) pumps which are smaller and lighter than single-stroke pumps but it is sensitive to vapor lock in which pump cylinder is filled with gas and the compression ratio of the pump is insufficient to raise the pressure of the compressed gas to ambient pressure and eventually caused the pump to cease. On the other hand, Slocum used single-stroke pumps which do not need valving to provide bi-directional buoyancy control and are immune to vapor lock.

Spray and Slocum are made up of aluminum hulls to resist external pressure and provide a streamlined hydrodynamic shape whereas Seaglider uses a compound hull with a flooded fiberglass fairing which provides a streamlined laminar-flow shape while an interior aluminium hull resists pressure [13]. All these three gliders maneuver underwater using a combination of a 3-axis magnetometer and a bubble-level. Besides, the pitch angle and dive angle of the three gliders are adjusted by shifting internal mass fore and aft.

CHAPTER 3

METHODOLOGY

This project methodology is important as all the design flow and development of the governing equations related to hydrodynamics forces and buoyancy concept of the glider are discussed. Brief description is given on each procedure carried out in the completion of the project. The project is planned to be accomplished in the following four developmental stages. For better understanding of research methodology process, flow chart of the project is shown in Figure 1.

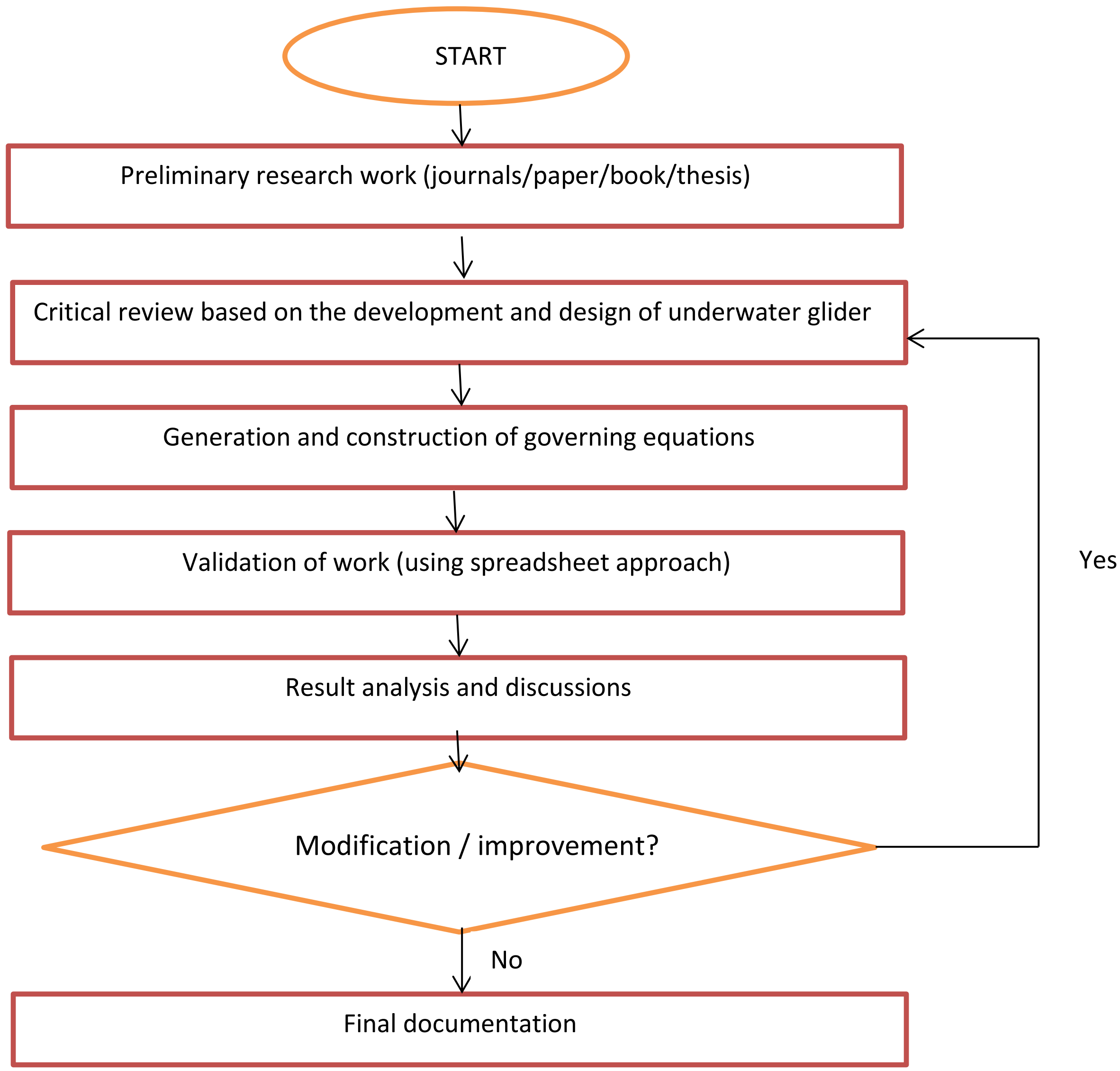

Figure 1 : Flow chart of project

The methodology in accomplishing this project is briefly reviewed to have a rough idea on how it is achieved. The author has divided the overall tasks to four stages. The project begins with some preliminary research work on the related topic, for instance journals or books written on AUV and underwater gliders. Subsequently, critical review on the development and design of underwater glider will be thoroughly looked into. This includes generating new idea on the design or doing some modifications on the existing design and governing equations corresponding to the parameters involved. Tools or software that is used throughout this project is Microsoft Excel. Spreadsheet analysis and verification is done next and improvement is made wherever necessary. In the last stage, final documentation is made for future reference.

3.1 Preliminary research work

Previous researches relating to underwater glider are studied during this stage in order to gain more understanding on how the glider functions underwater. Information and data on the related topics from different sources such as journals, books, articles and patent office are read, understood and collected for future reference.

3.2 Critical review based on the development and design of underwater glider

As the name suggests, critical review is carried out by gathering and interpret all the information obtained from the preliminary research work. Subsequently, generation of governing equations for underwater glider design that can carry an amount of payload is developed. This is done by analysing the dynamics of underwater gliders through few parameters such as the gliders' configuration and geometry, the forces of gravity and buoyancy and some other parameters which include lift and drag forces.

3.3 Spreadsheet analysis and verification

Evaluation on the design and related governing equations is done in this stage. The mathematical equations are constructed and should meet the requirements of the project. Spreadsheet approach is used for the analysis study and validation of the project is done through comparison of the result obtained from the analysis done with the existing parameters obtained from some previous study on underwater glider. Modification and improvement is made, if necessary before entering the final stage.

3.4 Final documentation

All information is compiled and systematic approach to design and development of underwater glider are documented at this stage. This task shall be done in proper manner as it serves as future reference for those who are interested to further study/research on this topic. Gantt chart for both Final Year Project I and II can be referred in Appendices C and D.

CHAPTER 4

CRITICAL REVIEW

4.1 Critical review analysis

As mentioned earlier in the previous chapters, this project focused on the governing equations underlying the principles of underwater glider. It is pursued by going into each element thoroughly to see in details the parameters that influence the dynamic study of the underwater glider. In consideration of the development of mathematical equations of underwater glider, the components of its system are represented by idealized elements that have the essential characteristics of the real components and whose behaviour can be described by mathematical equations. The following functional parameters of underwater glider are chosen based on evaluation of the attributes that contribute to change in buoyancy due to the amount of payload carried and the hydrodynamic forces that are affected by the adjustment of wings (wing area and wing span) as well as lift and ratio.

The design process starts with the underwater glider's intended purpose. Underwater gliders are commonly used for oceanographic purpose. However, the aim of this project is to provide a database for the design and development of underwater glider that are able to carry a certain amount of payload. Thus, in order to design underwater glider that is able to carry a payload, the author have to identify the input parameters and find answers to the following questions:

- What is the total mass of the underwater glider, together with the payload?
- What is the dimension of underwater glider that is able to support the payload weight?
- What is the optimum dimension or design of the wings to ensure that it can be adjusted to aid in horizontal movement of the underwater glider?

Boundary of this project is set to focus on the mathematical equations underlying the principle and characteristics of the underwater glider that are able to carry a certain amount of payload. The main aspects to be considered for the underwater glider design include:

- Mass
- Buoyancy
- Hydrodynamic
- Structure

4.2 Mass

Mass of underwater glider is the common parameter that links all aspects of the glider design such as hydrodynamics and its structure. An underwater glider is derived from various factors such as fixed mass that is uniformly distributed throughout the body of the glider (m_h), fixed point mass that may be off- set from the center of buoyancy (m_w), variable ballast point mass (m_b) and moving internal point mass ($\bar{m}$) as well as the payload weight that the underwater glider shall carry.

As stated by J.G. Graver and N.E. Leonard in [7], [10] and [11], gliders are described with simple body and wing shape. The total stationary mass of the glider, m_s (also referred to as body mass) is the sum of three terms:

Equation 1 : Total stationary mass of glider

$$m_s = m_h + m_w + m_b$$

where m_h is a fixed mass that is uniformly distributed throughout the body of the glider,
m_w is a fixed point mass that may be off- set from the center of buoyancy (CB),
m_b is the variable ballast point mass.

4.3 Buoyancy

The mass of the displaced fluid is denoted 'm' and the mathematical definition of the net buoyancy is;

Equation 2: Net buoyancy

$$m_o = m_v - m$$

this expression, it indicates that the glider is negatively (positively) buoyant if m_o is positive (negative). The different masses and position vectors are illustrated in Figure2. The vector from the CB to the point mass m_w is r_w. The vector from the CB to the variable ballast mass m_b is r_b. The moving internal point mass is $\bar{m}$. The vector $r_p(t)$ describes the position of this mass with respect to the CB at time t [7].

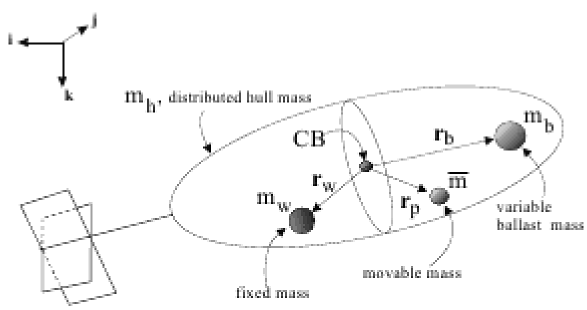

Figure 2: Glider Mass Definition [7]

Inflatable bladder is one of the commonly used buoyancy actuator for underwater gliders. This bladder is normally inflated with oil which caused the buoyant force on the vehicle increases; whereas when the bladder is deflated, the buoyant force on the vehicle decreases [14]. The moving mass actuator provides attitude control in pitch and roll by moving the vehicle center of mass relative to the center buoyancy [10].

4.4 Hydrodynamics forces

Study on hydrodynamic of underwater glider involves the properties and motion of the fluid in the surrounding that come into contact to it and forces which are acting on its body as it travel underwater. Vertical motion of underwater glider can be converted to horizontal motion provided that lift (*L*) is produced by the wing that acts perpendicular to the trajectory and is inclined in the direction of the vertical forces of gravity (upward for positive net buoyancy and downward for negative net buoyancy). Figure 3 below basic model of underwater glider with force balance and energetic of gliding path. S. A. Jenkins et al. stated that the vertical motion results from a descending glide slope for gliders in air or underwater if the net buoyancy is negative and is referred to as sink rate (*w*). Unlike gliders in air, underwater gliders can have ascending glide slopes if the net buoyancy is positive, producing a negative sink rate (-*w*).

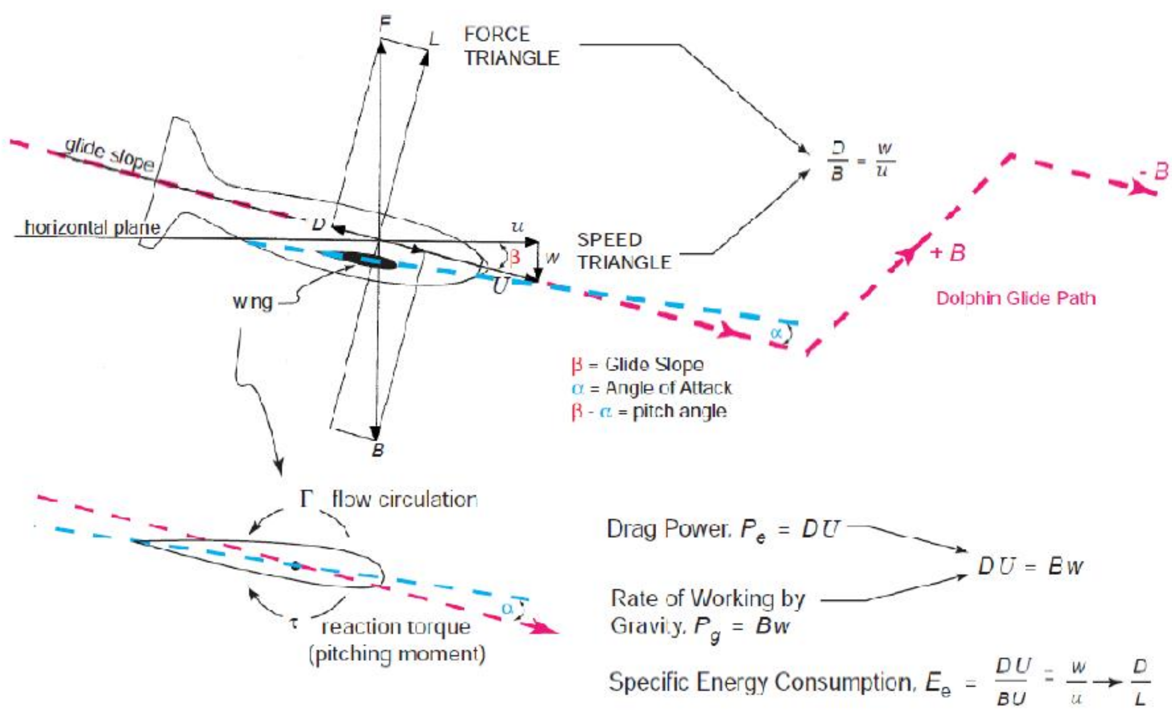

Figure 3: Force balance and energetic of gliding flight [12]

where B = net buoyancy,

L = lift,

D = drag,

F = resultant of lift and drag,

u = horizontal velocity,

w = vertical velocity,

U = glide velocity = resultant of horizontal and vertical,

T= flow circulation,

τ = pitch moment

The two equations as described below are used to calculate the lift and drag forces:

Equation 3: Drag force

$$F_D = -\frac{1}{2}\rho A_o \upsilon^2 C_D$$

Equation 4: Lift force

$$F_L = -\frac{1}{2}\rho A_p \upsilon^2 C_L$$

Given that C_D is drag coefficient

C_L is lift coefficient

V is the velocity of fluid

A is the reference area (cross section) for calculating lift or drag force

S. A. Jenkins et al. also mentioned that (as referring to Figure 3), during each of the descending or ascending slopes of the dolphin glide path, the power needed to overcome drag ($Pe = DU$) is equal to the rate of working by gravity acting down (or up) the glide slope ($Pe = Bw$). Thus, *Equation 5: Relationship between power to overcome drag, glider speed and net buoyancy of glider*

$$Pe = DU = Bw$$

where Pe is the power needed to overcome drag

D is the force of drag in Newton

U is the glider speed

B is the net buoyancy

w indicates the sink rate (if the net buoyancy is positive, negative sink rate (-*w*) is produced)

As the force triangle and the speed triangles in Figure 3 are proportional, the power expenditure per meter travelled scales is direct proportion to the glide slope (w/u ~ D/L), or inversely with the lift-drag ratio (L/D).

4.5 Structure

Common configuration of underwater glider includes:

- A hull, a long body, normally cylindrical and tapered or rounded at the end to make its shape hydro-dynamically smooth. The hull may contain battery, ballast tank, pump and payload that the underwater glider shall carry.
- Horizontal stabilizer or also known as elevator which is mounted at the tail of underwater glider. It is used to stabilize the underwater glider's pitch which controls the body to tilt up or down. Whereas vertical stabilizer which is also mounted at the tail of underwater glider, near the horizontal stabilizer and it is typically protruding above the glider. It acts as a stabilizer that controls the yaw of the underwater glider (for turning left or right motion).
- Wing that controls the underwater glider's movement while tilting to the left or to the right.

4.5.1 Wing design

Wing provides necessary lift as glider travel underwater and its geometry affects every aspect of the glider movement. The wing also stabilizes the underwater glider's movement while tilting to the left or to the right. In order to minimize drag, the wing design shall have high aspect ratio. As a basic design, the following parameters are considered:

- Wingspan length, S
- Cord length, C

From the given parameters, the wing area of the underwater glider and its aspect ratio can be found. Note: M is loaded mass in kilogram.

Equation 6: Wing area

$$\text{Wing area, } A_w = (0.165)M^{2/3} \text{ (based on square-cube law [12])}$$

$$= \text{wingspan, } S \text{ X chord, } C$$

Equation 7: Aspect ratio

$$\text{Aspect ratio, } AR = S^2/A_w$$

4.5.2 Horizontal and vertical stabilisers

As we obtained design-dimension for UG wing area and wing span, we shall compute out the parameters for both horizontal and vertical stabilisers as follows and the calculations of the parameters can be referred in appendix B:

Table 1: Mathematical equations for the determination of stabilisers' parameters

Parameters	Notation	Equation involved
Wing area	A_w	$(0.165)M^{2/3}$
Wing Span	S	$Sqrt(AR*A_w)$
Horizontal stabiliser chord	C_{HS}	Approximately 85% of C
Horizontal stabiliser span	S_{HS}	Approximately 40% of S
Horizontal stabiliser area	A_{HS}	C_{HS} X S_{HS}
Vertical stabiliser chord	C_{VS}	Approximately Equal to C_{HS}
Vertical stabiliser height	H_{VS}	Approximately 43% of S_{HS}
Vertical stabiliser area	A_{VS}	C_{VS} X H_{VS}

CHAPTER 5

RESULT AND DISCUSSION

Based on some assumptions and analysis that had been done by researchers in their previous studies, a data spreadsheet is created to provide specifications of underwater glider that is designed for payload delivery. All the identified elements in previous section are tabulated and shown in this section.

5.1 Glider Overall Mass

As stated in previous section, gliders are described with simple body and wing shape. The total stationary mass of the glider, m_s (also referred to as body mass) is the sum of three terms:

$$m_s = m_h + m_w + m_b$$

However, our main objective is to design an underwater glider that function as payload delivery transportation for subsea intervention. Thus, the total mass of the vehicle is then

Equation 8: Total mass of glider

$$\begin{aligned} m_v &= (m_h + m_w + m_b) + \bar{m} + m_p \\ &= m_s + \bar{m} + m_p \end{aligned}$$

where m_p is the payload.

This is one of the first information that needs to be identified as to determine the glider volume that will lead to the identification of the glider wings' sizing. Further description will be done in section 6.2.

5.2 Net Buoyancy

As mentioned in previous section 5.3, inflatable bladder is one of the commonly used buoyancy actuator for underwater gliders. This bladder is normally inflated with oil which caused the buoyant force on the vehicle increases; whereas when the bladder is deflated, the buoyant force on the vehicle decreases [14]. The net buoyancy of an underwater glider is equivalent to its loaded mass which can be computed as follows:

Equation 9: Loaded mass (net buoyancy) in kilogram

$$M \text{ (net buoyancy)} = \rho_{fluid(oil)}\, n_b\ V_o$$

where M is the loaded mass

ρ_{fluid} is fluid density and is set to be 900kg/m^3 for oil

n_b is the lung capacity factor of the glider (between range of 0.005-0.04)

V_o is the glider's volume in total

The selected range of payload mass to be focused in this project 100 kg to 1000 kg. Underwater glider is normally designed to be neutrally buoyant and this can be achieved by following Archimedes' principle which stated that when an object is neutrally buoyant, the volume of the displaced fluid = volume of the object. This principle aids in the understanding the concept in determining the expected volume of underwater (UW) glider. Glider volume determination based on glider total mass is tabulated in Table 6 (refer Appendix A) where

Equation 10: Glider volume

$$\text{Glider volume, } V_o = m_v / \rho_{seawater}$$

Given $\rho_{seawater}$ is density of seawater. As it is known, density of pure water is 1000 kg/m^3 but seawater is denser due to the salt content in it. Its density is influenced by two main factors namely the temperature and salinity of the water. Seawater is denser as the temperature drops and as the salinity increases. However, in our calculation as tabulated in Table 6, $\rho_{seawater}$ is assumed to be constant (1025 kg/m^3). Note that it is made so to simplify the whole determination process.

5.3 Hydrodynamic forces

Design of an underwater glider depends on its functional purpose. For instance, the existing legacy gliders are designed for steeper glide path angles and lower lift/drag ratios while in the other hand the X-RAY Liberdade gliders are designed for high lift/drag performance and minimum glide path angle [12]. Based on Figure 3 in section 5.4, there is a special relationship between lift and drag (L/D) ratio, horizontal and vertical speed of glider and the angle of glide path as described below:

Equation 11: Relationship between L/D ratio with horizontal and vertical speed of glider

$$L/D = u/w$$

where L/D is lift and drag ratio,

u is the horizontal speed of the glider, and

w is the vertical speed of the glider

Both horizontal and vertical speed of glider is influenced by the glide path angle taken. Horizontal velocity of the glider is indicated as cos β whereas vertical velocity of glider is sin β. Calculations are done in excel spreadsheet using the mentioned relations and they are as tabulated in Table 2. It also reveals that glide path angles more than ten degrees require operational lift/drag ratios less than 5 (as data tabulated in Table 2).

Table 2: Relationship between glide angle with horizontal and vertical speed of glider and its L/D ratio

glide angle (°)	horizontal speed, u (cos β)	vertical speed, w (sin β)	L/D ratio
1	1.000	0.017	57.290
5	0.996	0.087	11.430
10	0.985	0.174	5.671
15	0.966	0.259	3.732
20	0.940	0.342	2.747
25	0.906	0.423	2.145
30	0.866	0.500	1.732
35	0.819	0.574	1.428
40	0.766	0.643	1.192
45	0.707	0.707	1.000
50	0.643	0.766	0.839
55	0.574	0.819	0.700
60	0.500	0.866	0.577
65	0.423	0.906	0.466
70	0.342	0.940	0.364
75	0.259	0.966	0.268
80	0.174	0.985	0.176
85	0.087	0.996	0.087
90	0.000	1.000	0.000

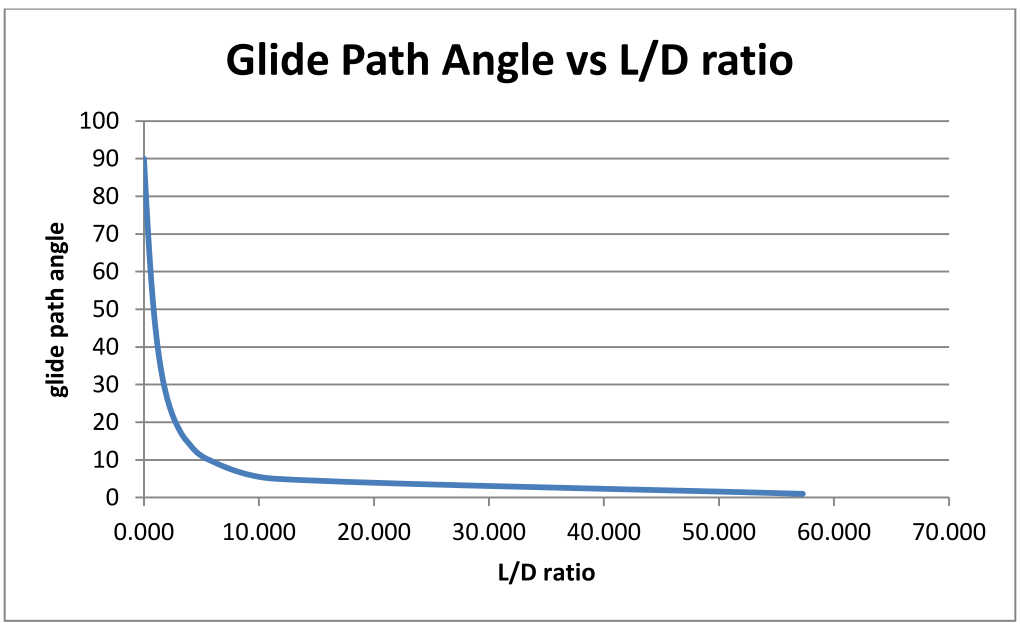

Figure 4 : Glide angle vs L/D ratio

A data spreadsheet with following variables is generated based on few parameters of the glider as shown in Table 6 (refer to Appendix A).

Variable(s)	Value
Drag coefficient, Cd	0.003
Fluid density (oil) (kg/m^3)	900
Seawater density (kg/m^3)	1025
Glide angle, $\boldsymbol{\beta}$ (^{o})	35
L/D ratio	1.4
Aspect ratio, AR	14

Table 6 shows the extrapolated result of identified parameters based on spreadsheet analysis done. The analysis is executed according to the data approximately similar to legacy glider as the vehicle characteristics and performances are applicable in payload delivery [12].

5.4 Glide Speed

According to [12], equation for horizontal (cross country) speed is as follow:

Equation 12: Horizontal speed

$$u_{max} = \left(\frac{B \sin\beta}{0.5\,\rho C_d}\right)^{\frac{1}{2}} (\cos\beta)$$

where B is the net buoyancy force, which is equivalent to loaded mass in kilogram

β = glide path angle (in degree)

C_d = drag coefficient which is set to 0.003

It is vital to identify the maximum horizontal speed of the glider in order to determine the maximum glide speed as this information will enable us to know the operation capability of the glider at the mentioned speed. It is stated that, at u = u_{max}, the trigonometric glide path factor cos β $(\sin \beta)^{1/2}$ is always 0.6, (Graver,2003). A dimensionless speed function are calculated in excel spreadsheet and is tabulated as in Table 3 and a graph of speed function versus the glide angle is generated as shown in Figure 5.

Table 3: Relationship between glide angle with dimensionless speed function

glide angle (^{o})	speed function	glide angle (^{o})	speed function
1	0.132	45	0.595
5	0.294	50	0.563
10	0.410	60	0.465
15	0.491	65	0.402
20	0.550	70	0.332
25	0.589	75	0.254
30	0.612	80	0.172
35	0.620	85	0.087
40	0.614	90	0.000

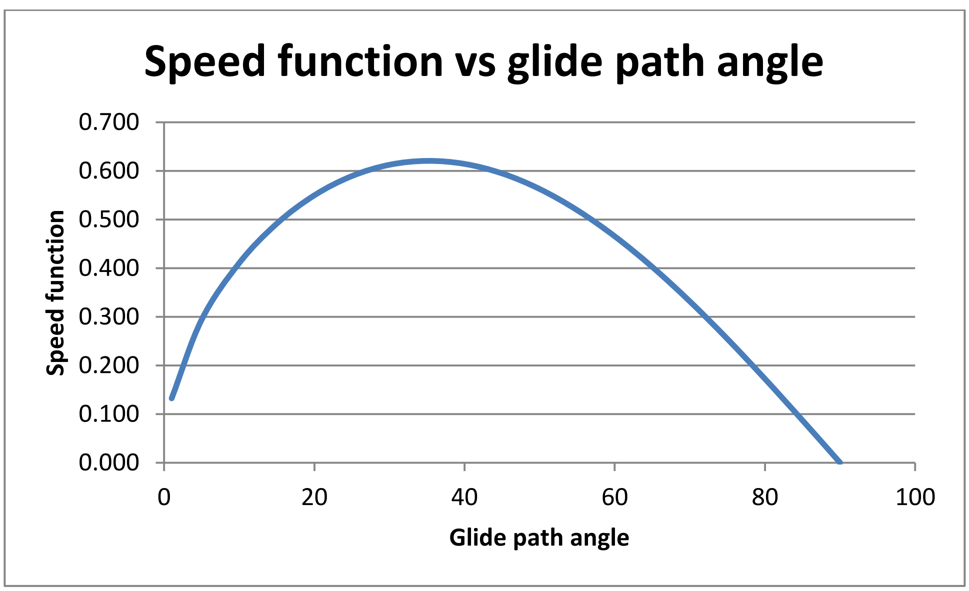

Figure 5: Speed Function, cos β (sin β)^1/2 vs glide path angle, β

It reveals in Figure 5 that maximum horizontal speed, u_{max} ,is always obtained at a 35^o glide path angle, regardless of vehicle shape or other hydrodynamic properties [12]. As tabulated in Table 3, at glide path angle of $\beta = 35^o$, the speed function is at the highest, around 0.62, which agreed to what had been stated in (Graver, 2003) where the speed function is at the highest, around 0.6.

Referring to Figure 4 and 5, the glider requirement for maximum horizontal speed should minimize drag at a glide angle near 35 degrees, which in other term means to increase the lift and drag (L/D) ratio by designing glider with least drag possible and sufficient lift for smooth motion. Lift and drag (L/D) value at fastest glide angle (35^o) is 1.4 as obtained in Table 2. This value is used in the further calculation of glider parameters.

S. A. Jenkins (et.al) stated in [12] that the maximum glider horizontal speed can also be analyzed in the function of glider volume, geometry and ballast tank size where ballast tank size is normally associated with lung capacity factor, n_b = ratio of net buoyancy volume to displaced volume.

The maximum glide speed has a unique relation to vehicle volume and capacity factor as described below. Note: In the underwater glider application, the loaded mass is supplied by the buoyancy engine:

Equation 13: Maximum glide speed

$$u_{max} \sim 0.6(55.6\, g\, n_b)^{\frac{1}{2}} {V_o}^{1/6}$$

by substituting B with Mg

$M = \rho\, n_b\, V_o$

$\cos \beta\ (\sin \beta)^{1/2} = 0.6$ (as obtained from Table 3)

into equation 10. Outputs obtained from the excel spreadsheet calculations are tabulated in Table 4.

Table 4: relationship between glider volume, lung capacity factor and maximum horizontal speed of glider

Glider volume, V_o	Lung capacity factor, n_b						
	0.005	0.01	0.05	0.1	0.2	0.3	0.4
	Maximum horizontal speed, u_{max}						
0	0	0	0	0	0	0	0
0.098	0.672	0.951	2.126	3.007	4.252	5.208	6.013
0.195	0.755	1.067	2.386	3.375	4.773	5.845	6.749
0.293	0.807	1.142	2.553	3.611	5.106	6.254	7.221
0.390	0.847	1.198	2.679	3.788	5.357	6.561	7.576
0.488	0.879	1.243	2.780	3.932	5.560	6.810	7.863
0.585	0.906	1.282	2.866	4.053	5.732	7.020	8.106
0.683	0.930	1.315	2.940	4.158	5.881	7.202	8.317
0.780	0.951	1.345	3.007	4.252	6.013	7.365	8.504
0.878	0.970	1.371	3.066	4.336	6.132	7.511	8.672
0.976	0.987	1.396	3.120	4.413	6.241	7.644	8.826

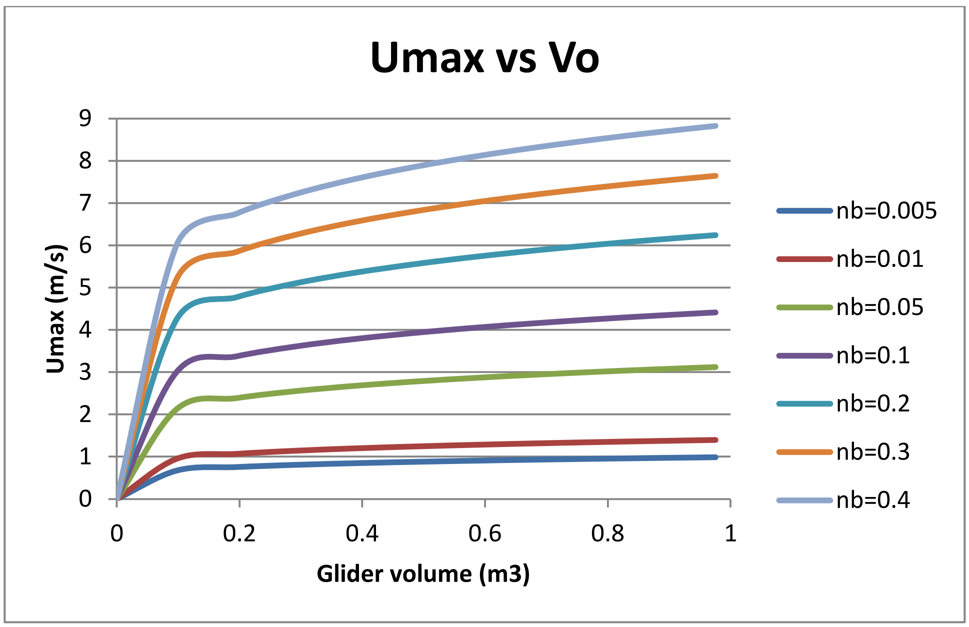

Figure 6: Maximum cross country speed u_{max} as a function of total vehicle volume, V_o for various lung capacity factors, nb; where, $n_b = V_{buoyancy} / V_o$

Based on the Equation 11 as well as Figure 6, there are two possible ways to increase the maximum horizontal velocity of a glider [12]:

I. The maximum horizontal speed is directly increases by the factor of $n_b^{(1/2)}$, if the glider volume is kept constant and lung capacity factor of glider is increased.

II. The maximum horizontal speed is directly increases by the factor of $V_o^{(1/6)}$, if the lung capacity factor, n_b is kept constant and glider volume is changed.

5.5 Wing Structure

Consequent to elements discussed in previous sections, the dimension of glider's wings can be identified by relating the wing dimensions scale with loaded mass by a principle known as the square-cubed law originally suggested by Cayley and critiqued later in the *Journal of Aircraft* by Cleveland (1970) which specifies that:

Equation 14: Wing area (based on square-cubed law)

$$\text{Wing area : } A \sim 0.165\ M^{(2/3)}$$

Equation 15: Aspect ratio in terms of wing span, wing area and its chord

$$\text{Aspect ratio (AR) : } \frac{(\text{wing span,S})^2}{\text{wing area,A}} = \frac{wing\ span,S}{chord,C}$$

Assuming aspect ratio, AR = 14, Table 6 (refer to Appendix A) reveals in order to achieve glide speed approximately 9.4 m/s at lung capacity factor of 0.4 and total vehicle volume, V_o of 0.98 m^3 , the glider requires almost up to 10.7 meter of wing span and wing area of 8.2 m^2.

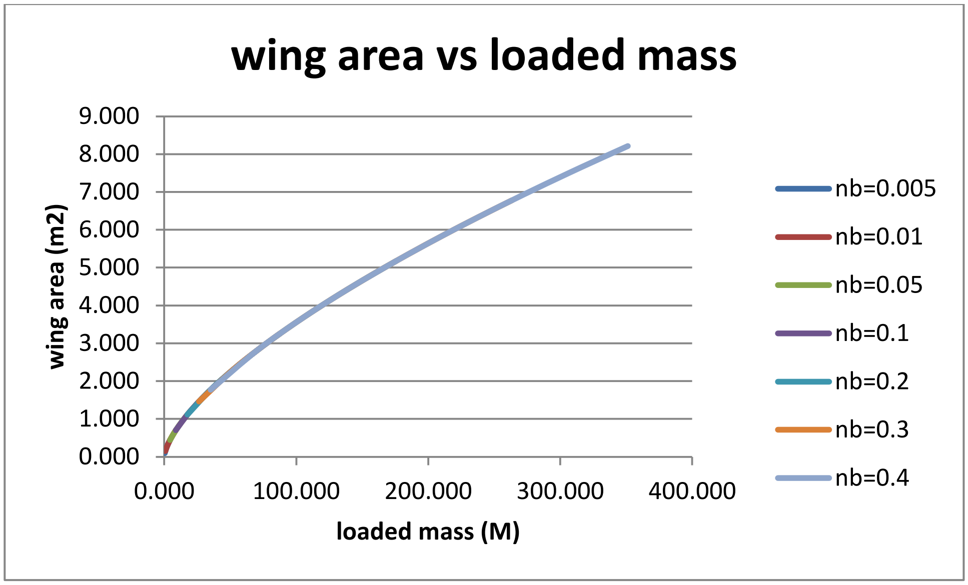

Figure 7: Wing area versus loaded mass

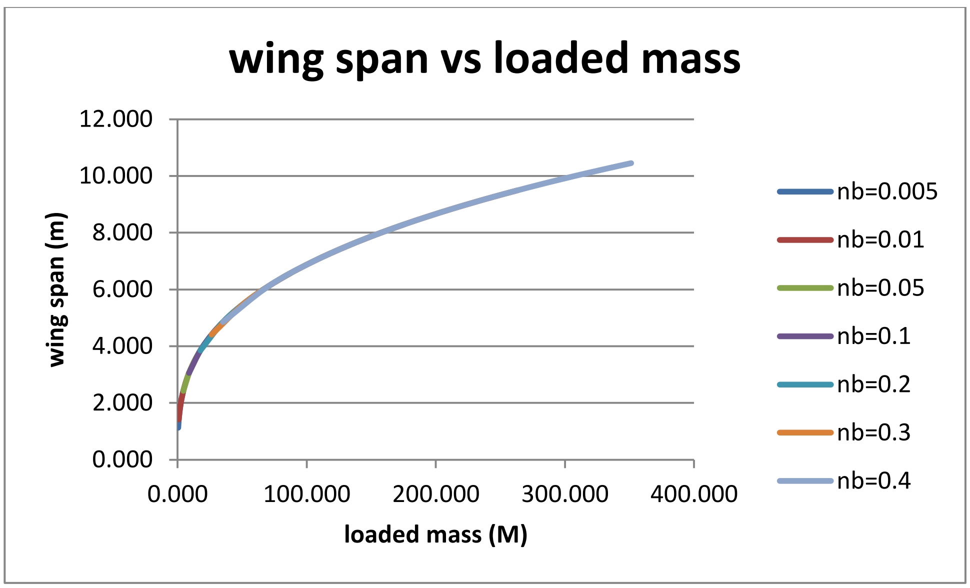

Figure 8: Wing span versus loaded mass

Figure 7 and 8 show the characteristic wing dimensions as a function of loaded mass, M for variation in wing span with loaded mass and variation in wing area, A with loaded mass. It also reveals that as the loaded mass increases with the increment of lung capacity factor, n_b the wing span and wing area need to be increased as well in order to support the increment of the loaded mass.

5.5.1 Verification of output from spreadsheet approach

Validation is carried out by doing comparison between outputs obtained from spreadsheet approach with the existing underwater glider; Spray's parameters such as its wing span, wing area, horizontal speed and glide speeds which are extracted from Marine Technology Society Journal [13]. Table 5 below summarizes the comparison of the outputs from spreadsheet analysis provided the lung capacity factor is 0.01.

Table 5: Comparison between spreadsheet outputs to the existing parameters

Parameters	Existing underwater glider; Spray [13]	Outputs from spreadsheet analysis	Percentage error (%)
Vehicle mass (kg)	54.5	Set to 54.5	-
Wing span (m)	1.1	1.189	7.49
Wing area (m^2)	0.12	0.101	18.81
Horizontal speed (m/s)	0.25-0.35 (take 0.35)	0.346	1.16

Table 5 shows that the spreadsheet approach's outputs are comparable to the existing underwater glider's parameters (given percentage error is less than 20%). Consequent to this, the spreadsheet approach is validated provided the lung capacity factor is 0.01 and glide angle is 35 degree.

CHAPTER 6

CONCLUSION AND FUTURE WORK

In line with the focus to develop mathematical model to determine the characteristics of underwater glider that are able to carry an amount of payload, related governing equations were addressed in previous sections. Study on the dynamics of underwater glider was also done to better analyse the concept and principles underlying the design of underwater gliders that is carrying a payload. Consequently, mathematical equations were developed to guide the design of an underwater glider and to provide a database of model parameter values for various sizes of underwater glider with respect to the weight of payloads they carry.

To expand the database parameters for the design and development of underwater glider, few aspects need to be considered. These include the total mass of the underwater glider with payload, lung capacity factor, glide angle and L/D ratio. Based on previous researches/studies and some hydrodynamics assumptions, governing equations relating to the design of underwater glider was programmed into Microsoft Excel spread sheets.

The outputs of the spread sheet were compared to the existing underwater glider's parameters. The existing underwater glider's parameters were obtained from Marine Technology Society Journal [13]. It is shown that the results are comparable with percentage error less than 20%.

However, due to the lack of previous results on the similar study, some parameters for the new design of underwater glider were not properly validated. Therefore, for the future work, further optimization of the glider body and wings shall be made and having these parameters in hand, a prototype should be made and experimentally tested to see whether the underwater glider meets its functionality and purpose of carrying a payload for underwater intervention.

REFERENCES

[1] Xiaoming Wang, Jianzhong Shang, Zirong Luo, Li Tang, Xiangpo Zhang, Juan Li. Review of power systems and environmental energy conversion for unmanned underwater vehicles. Renewable and Sustainable Energy Reviews 16 (2012) 1958-1970

[2] E.O. Rogers, J.G. Genderson, W.S. Smith, G.F. Denny, and P.J. Farley, “Underwater acoustic glider,” *Proceedings of IGARSS ’04*, Vol. 3, pp. 2241-2244, 2004.

[3] H. Stommel, “The Slocum mission,” *Oceanography*, Vol. 2, No. 1, pp.22–25, 1989.

[4] D. C. Webb, P. J. Simonetti, and C.P. Jones, “SLOCUM, an underwater glider propelled by environmental energy,” *IEEE Journalof Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol. 26, No. 4, pp. 447–452, 2001.

[5] J. Sherman, R. E. Davis, W. B. Owens, and J. Valdes, “The autonomous underwater glider ‘Spray’,” *IEEE Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol. 26, No. 4, pp. 437–446, 2001.

[6] C. C. Eriksen, T. J. Osse, T. Light, R. D. Wen, T. W. Lehmann, P. L. Sabin, J. W. Ballard, and A. M. Chiodi, “Seaglider: A long range autonomous underwater vehicle for oceanographic research,” *IEEE Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol. 26, No. 4, pp.424–436, 2001.

[7] J.G. Graver, R. Bachmayer, and N.E. Leonard, “Underwater glider model parameter identification[C],” *Proc.13th Int. Symp. on Unmanned Untethered Submersible Technology (UUST), AUG*,Vol. 5,2003.

[8] N. Mahmoudian, J. Geisbert, and C. Woolsey, “Dynamics & control of underwater gliders I: steady motions,” http://www.unmanned.vt.edu/discovery/reports/VaCAS_2007_01.pdf, 2007

[9] C.K. Ambler, “Design of an Underwater Vertical glider for Subsea Equipment Delivery.” Massachusetts Institute of Technology, February 2010.

[10] J.G. Graver and N.E. Leonard. Underwater glider dynamics and control. In *Proc. 12th Int. Symposium on Unmanned Untethered Sub- mersible Tech.*, Durham, NH, 2001.

[11] N.E. Leonard and J.G. Graver. Model-based feedback control of autonomous underwater glid-ers. *IEEE Journal of Oceanic Engineering, Spe-cial Issue on Autonomous Ocean Sampling Net-works*, 26(4):633–645, 2001

[12] S. A. Jenkins, D. E. Humphreys, J. Sherman, J. Osse, C. Jones, N. E. Leonard, R. Bachmayer, J. Graver, T. Clem, P. Carroll, P. Davis, J. Berry, P.Worley, and J. Wasyl, “Underwater glider system study.” Technical Report, Office of Naval Research, 2003.

[13] Daniel L. Rudnick, Russ E. Davis, Charles C. Eriksen, David M. Fratantoni, Mary Jane Perry, “Underwater gliders for ocean research.” Marine Technology Society Journal.

[14] Jesse Stuart Geisbert, “Hydrodynamic Modeling for Autonomous Underwater Glider Vehicles using Computational and Semi-empirical Methods.” Thesis, Blacksburg, Virginia, 2007.

APPENDICES

APPENDIX A: Spreadsheet approach to determine wing area and wing span depending on total vehicle mass with certain amount of payload

Table 6: Excel spreadsheet approach for the determination of wing area and wing span

Vehicle mass (+payload) (kg)	Glider volume, Vo (m^3)	Lung capacity factor, n_b	Loaded mass M (kg)	Maximum horizontal speed, umax (m/s)	Vertical speed, w (m/s)	Glide speed, U (m/s)	Wing area, A_w (m^2)	Wing span, S (m)
54.5 (Existing UG; Spray)	0.053	0.005	0.239	0.245	0.175	0.301	0.064	0.944
		0.01	0.479	0.346	0.247	0.425	0.101	1.189
		0.05	2.393	0.774	0.553	0.951	0.295	2.033
		0.1	4.785	1.094	0.782	1.345	0.469	2.561
		0.2	9.571	1.548	1.106	1.902	0.744	3.227
		0.3	14.356	1.896	1.354	2.330	0.975	3.694
		0.4	19.141	2.189	1.564	2.690	1.181	4.066
100	0.098	0.005	0.439	0.332	0.237	0.407	0.095	1.155
		0.01	0.878	0.469	0.335	0.576	0.151	1.455
		0.05	4.390	1.048	0.749	1.288	0.442	2.489
		0.1	8.780	1.483	1.059	1.822	0.702	3.136
		0.2	17.561	2.097	1.498	2.577	1.115	3.951
		0.3	26.341	2.568	1.834	3.156	1.461	4.522
		0.4	35.122	2.965	2.118	3.644	1.770	4.977
200	0.195	0.005	0.878	0.469	0.335	0.576	0.151	1.455
		0.01	1.756	0.663	0.474	0.815	0.240	1.834
		0.05	8.780	1.483	1.059	1.822	0.702	3.136
		0.1	17.561	2.097	1.498	2.577	1.115	3.951

		0.2	35.122	2.965	2.118	3.644	1.770	4.977
		0.3	52.683	3.632	2.594	4.463	2.319	5.698
		0.4	70.244	4.193	2.995	5.153	2.809	6.271
300	0.293	0.005	1.317	0.574	0.410	0.706	0.198	1.666
		0.01	2.634	0.812	0.580	0.998	0.315	2.099
		0.05	13.171	1.816	1.297	2.231	0.920	3.589
		0.1	26.341	2.568	1.834	3.156	1.461	4.522
		0.2	52.683	3.632	2.594	4.463	2.319	5.698
		0.3	79.024	4.448	3.177	5.466	3.038	6.522
		0.4	105.366	5.136	3.668	6.311	3.681	7.179
400	0.390	0.005	1.756	0.663	0.474	0.815	0.240	1.834
		0.01	3.512	0.938	0.670	1.152	0.381	2.310
		0.05	17.561	2.097	1.498	2.577	1.115	3.951
		0.1	35.122	2.965	2.118	3.644	1.770	4.977
		0.2	70.244	4.193	2.995	5.153	2.809	6.271
		0.3	105.366	5.136	3.668	6.311	3.681	7.179
		0.4	140.488	5.930	4.236	7.288	4.459	7.901
500	0.488	0.005	2.195	0.741	0.529	0.911	0.279	1.975
		0.01	4.390	1.048	0.749	1.288	0.442	2.489
		0.05	21.951	2.344	1.674	2.881	1.294	4.256
		0.1	43.902	3.315	2.368	4.074	2.053	5.362
		0.2	87.805	4.688	3.349	5.761	3.260	6.755
		0.3	131.707	5.742	4.101	7.056	4.271	7.733
		0.4	175.610	6.630	4.736	8.148	5.174	8.511
600	0.585	0.005	2.634	0.812	0.580	0.998	0.315	2.099
		0.01	5.268	1.148	0.820	1.411	0.500	2.645
		0.05	26.341	2.568	1.834	3.156	1.461	4.522
		0.1	52.683	3.632	2.594	4.463	2.319	5.698
		0.2	105.366	5.136	3.668	6.311	3.681	7.179
		0.3	158.049	6.290	4.493	7.730	4.823	8.217

		0.4	210.732	7.263	5.188	8.926	5.843	9.044
700	0.683	0.005	3.073	0.877	0.626	1.078	0.349	2.210
		0.01	6.146	1.240	0.886	1.524	0.554	2.784
		0.05	30.732	2.774	1.981	3.409	1.619	4.761
		0.1	61.463	3.922	2.802	4.820	2.570	5.998
		0.2	122.927	5.547	3.962	6.817	4.079	7.557
		0.3	184.390	6.794	4.853	8.349	5.345	8.651
		0.4	245.854	7.845	5.604	9.641	6.475	9.521
800	0.780	0.005	3.512	0.938	0.670	1.152	0.381	2.310
		0.01	7.024	1.326	0.947	1.630	0.605	2.911
		0.05	35.122	2.965	2.118	3.644	1.770	4.977
		0.1	70.244	4.193	2.995	5.153	2.809	6.271
		0.2	140.488	5.930	4.236	7.288	4.459	7.901
		0.3	210.732	7.263	5.188	8.926	5.843	9.044
		0.4	280.976	8.387	5.990	10.306	7.078	9.955
900	0.878	0.005	3.951	0.995	0.710	1.222	0.412	2.403
		0.01	7.902	1.406	1.005	1.728	0.655	3.027
		0.05	39.512	3.145	2.246	3.865	1.914	5.177
		0.1	79.024	4.448	3.177	5.466	3.038	6.522
		0.2	158.049	6.290	4.493	7.730	4.823	8.217
		0.3	237.073	7.704	5.503	9.467	6.320	9.407
		0.4	316.098	8.895	6.354	10.932	7.657	10.353
1000	0.976	0.005	4.390	1.048	0.749	1.288	0.442	2.489
		0.01	8.780	1.483	1.059	1.822	0.702	3.136
		0.05	43.902	3.315	2.368	4.074	2.053	5.362
		0.1	87.805	4.688	3.349	5.761	3.260	6.755
		0.2	175.610	6.630	4.736	8.148	5.174	8.511
		0.3	263.415	8.120	5.800	9.979	6.780	9.743
		0.4	351.220	9.377	6.698	11.523	8.214	10.723

APPENDIX B: Spreadsheet approach to determine stabilisers' parameters based on wing area and wing span's dimensions.

Table 7: Excel spreadsheet approach for the determination of wing area and wing span

Wing area	Wing span	Wing chord	HS_chord	HS_span	HS_area	VS_height	VS_cord	VS_area
0.064	0.944	0.067	0.057	0.377	0.022	0.162	0.057	0.009
0.101	1.189	0.085	0.072	0.476	0.034	0.204	0.072	0.015
0.295	2.033	0.145	0.123	0.813	0.100	0.350	0.123	0.043
0.469	2.561	0.183	0.156	1.024	0.159	0.441	0.156	0.069
0.744	3.227	0.230	0.196	1.291	0.253	0.555	0.196	0.109
0.975	3.694	0.264	0.224	1.478	0.331	0.635	0.224	0.142
1.181	4.066	0.290	0.247	1.626	0.401	0.699	0.247	0.173
0.095	1.155	0.083	0.070	0.462	0.032	0.199	0.070	0.014
0.151	1.455	0.104	0.088	0.582	0.051	0.250	0.088	0.022
0.442	2.489	0.178	0.151	0.995	0.150	0.428	0.151	0.065
0.702	3.136	0.224	0.190	1.254	0.239	0.539	0.190	0.103
1.115	3.951	0.282	0.240	1.580	0.379	0.679	0.240	0.163
1.461	4.522	0.323	0.275	1.809	0.497	0.778	0.275	0.214
1.770	4.977	0.356	0.302	1.991	0.602	0.856	0.302	0.259
0.151	1.455	0.104	0.088	0.582	0.051	0.250	0.088	0.022
0.240	1.834	0.131	0.111	0.733	0.082	0.315	0.111	0.035
0.702	3.136	0.224	0.190	1.254	0.239	0.539	0.190	0.103
1.115	3.951	0.282	0.240	1.580	0.379	0.679	0.240	0.163
1.770	4.977	0.356	0.302	1.991	0.602	0.856	0.302	0.259
2.319	5.698	0.407	0.346	2.279	0.788	0.980	0.346	0.339
2.809	6.271	0.448	0.381	2.508	0.955	1.079	0.381	0.411
0.198	1.666	0.119	0.101	0.666	0.067	0.287	0.101	0.029
0.315	2.099	0.150	0.127	0.840	0.107	0.361	0.127	0.046
0.920	3.589	0.256	0.218	1.436	0.313	0.617	0.218	0.135

1.461	4.522	0.323	0.275	1.809	0.497	0.778	0.275	0.214
2.319	5.698	0.407	0.346	2.279	0.788	0.980	0.346	0.339
3.038	6.522	0.466	0.396	2.609	1.033	1.122	0.396	0.444
3.681	7.179	0.513	0.436	2.871	1.251	1.235	0.436	0.538
0.240	1.834	0.131	0.111	0.733	0.082	0.315	0.111	0.035
0.381	2.310	0.165	0.140	0.924	0.130	0.397	0.140	0.056
1.115	3.951	0.282	0.240	1.580	0.379	0.679	0.240	0.163
1.770	4.977	0.356	0.302	1.991	0.602	0.856	0.302	0.259
2.809	6.271	0.448	0.381	2.508	0.955	1.079	0.381	0.411
3.681	7.179	0.513	0.436	2.871	1.251	1.235	0.436	0.538
4.459	7.901	0.564	0.480	3.160	1.516	1.359	0.480	0.652
0.279	1.975	0.141	0.120	0.790	0.095	0.340	0.120	0.041
0.442	2.489	0.178	0.151	0.995	0.150	0.428	0.151	0.065
1.294	4.256	0.304	0.258	1.702	0.440	0.732	0.258	0.189
2.053	5.362	0.383	0.326	2.145	0.698	0.922	0.326	0.300
3.260	6.755	0.483	0.410	2.702	1.108	1.162	0.410	0.477
4.271	7.733	0.552	0.469	3.093	1.452	1.330	0.469	0.624
5.174	8.511	0.608	0.517	3.404	1.759	1.464	0.517	0.756
0.315	2.099	0.150	0.127	0.840	0.107	0.361	0.127	0.046
0.500	2.645	0.189	0.161	1.058	0.170	0.455	0.161	0.073
1.461	4.522	0.323	0.275	1.809	0.497	0.778	0.275	0.214
2.319	5.698	0.407	0.346	2.279	0.788	0.980	0.346	0.339
3.681	7.179	0.513	0.436	2.871	1.251	1.235	0.436	0.538
4.823	8.217	0.587	0.499	3.287	1.640	1.413	0.499	0.705
5.843	9.044	0.646	0.549	3.618	1.987	1.556	0.549	0.854
0.349	2.210	0.158	0.134	0.884	0.119	0.380	0.134	0.051
0.554	2.784	0.199	0.169	1.114	0.188	0.479	0.169	0.081
1.619	4.761	0.340	0.289	1.904	0.550	0.819	0.289	0.237
2.570	5.998	0.428	0.364	2.399	0.874	1.032	0.364	0.376
4.079	7.557	0.540	0.459	3.023	1.387	1.300	0.459	0.596

5.345	8.651	0.618	0.525	3.460	1.817	1.488	0.525	0.781
6.475	9.521	0.680	0.578	3.809	2.202	1.638	0.578	0.947
0.381	2.310	0.165	0.140	0.924	0.130	0.397	0.140	0.056
0.605	2.911	0.208	0.177	1.164	0.206	0.501	0.177	0.088
1.770	4.977	0.356	0.302	1.991	0.602	0.856	0.302	0.259
2.809	6.271	0.448	0.381	2.508	0.955	1.079	0.381	0.411
4.459	7.901	0.564	0.480	3.160	1.516	1.359	0.480	0.652
5.843	9.044	0.646	0.549	3.618	1.987	1.556	0.549	0.854
7.078	9.955	0.711	0.604	3.982	2.407	1.712	0.604	1.035
0.412	2.403	0.172	0.146	0.961	0.140	0.413	0.146	0.060
0.655	3.027	0.216	0.184	1.211	0.223	0.521	0.184	0.096
1.914	5.177	0.370	0.314	2.071	0.651	0.890	0.314	0.280
3.038	6.522	0.466	0.396	2.609	1.033	1.122	0.396	0.444
4.823	8.217	0.587	0.499	3.287	1.640	1.413	0.499	0.705
6.320	9.407	0.672	0.571	3.763	2.149	1.618	0.571	0.924
7.657	10.353	0.740	0.629	4.141	2.603	1.781	0.629	1.119
0.442	2.489	0.178	0.151	0.995	0.150	0.428	0.151	0.065
0.702	3.136	0.224	0.190	1.254	0.239	0.539	0.190	0.103
2.053	5.362	0.383	0.326	2.145	0.698	0.922	0.326	0.300
3.260	6.755	0.483	0.410	2.702	1.108	1.162	0.410	0.477
5.174	8.511	0.608	0.517	3.404	1.759	1.464	0.517	0.756
6.780	9.743	0.696	0.592	3.897	2.305	1.676	0.592	0.991
8.214	10.723	0.766	0.651	4.289	2.793	1.844	0.651	1.201

APPENDIX C: Final Year Project I Gantt Chart

No	FYP progress / activities	Week												
		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Selection of project topic: Development and Design of Underwater Glider													
2	Preliminary research work : Literature review on related topics													
3	Submission of extended proposal													
4	Project work 1: Familiarization to problem statement													
5	Project work 2: Critical review on development and design of underwater glider													
6	Project work 3: Further study on design													
7	Proposal defence													
8	Project work progress: Mathematical modelling related to underwater glider design													
9	Submission of draft of interim report													
10	Submission of interim report													

APPENDIX D: Final Year Project II Gantt Chart

No	FYP progress / activities	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Gather governing equations related to the design of UG														
2	Further analyse and generate a spreadsheet database for UD design and development														
3	Verification of some parameters through comparison with existing UG														
4	Submission of progress report														
5	Continue governing equations to design final shape														
6	Modify and generate new spreadsheet database with appropriate equations														
7	Compile results and make discussions on the topic for final documentation														
8	Poster presentation														
9	Submission of technical paper														
10	Viva presentation Submission of FYP final report														