



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**AN ANALYSIS OF UNDERSEA GLIDER
ARCHITECTURES AND AN ASSESSMENT OF
UNDERSEA GLIDER INTEGRATION INTO UNDERSEA
APPLICATIONS**

by

William P. Barker

September 2012

Thesis Advisor:
Second Reader:

John Osmundson
Steven Bousquet

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2012	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE An Analysis of Undersea Glider Architectures and an Assessment of Undersea Glider Integration into Undersea Applications			5. FUNDING NUMBERS	
6. AUTHOR(S) William P. Barker				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ___N/A___.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) Currently, buoyancy driven underwater gliders are deployed globally to gather oceanographic data from across the world's oceans. This thesis examines the utility of underwater gliders within the context of providing additional U.S. Navy capabilities. An extensive survey of available underwater gliders was undertaken and the resultant survey pool of ten gliders down selected to five gliders of fixed wing configuration. A comprehensive architectural analysis was then conducted of seven key architectural attributes of the five selected gliders. The architectural analysis compared various implementations of the key architectural attributes relative to desirable traits and capabilities for a notional U.S. Navy glider. Following the architectural analysis a proposed architecture for a U.S. Navy underwater glider was developed which includes a compendium of 'best' features gleaned from the architectural analysis. Drivers and rationale for selection of specific key architectural attributes and features are also provided. Additionally, a comparison of constraints and capabilities of underwater gliders is provided. Finally, a comparison of the current and proposed capabilities of underwater gliders versus other Autonomous Undersea Vehicles, specifically Unmanned Undersea Vehicles, is proffered.				
14. SUBJECT TERMS underwater glider, unmanned undersea vehicle (UUV), autonomous undersea vehicle (AUV), system architecture, underwater glider survey, architectural attributes, underwater glider recommendation for U.S. Navy, underwater glider system analysis			15. NUMBER OF PAGES 91	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

**AN ANALYSIS OF UNDERSEA GLIDER ARCHITECTURES AND AN
ASSESSMENT OF UNDERSEA GLIDER INTEGRATION INTO UNDERSEA
APPLICATIONS**

William P. Barker
Civilian, Department of the Navy
B.S., University of Rhode Island, 1983

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
September 2012**

Author: William P. Barker

Approved by: John S. Osmundson
Thesis Advisor

Steven Bousquet
Second Reader

Clifford Whitcomb
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Currently, buoyancy driven underwater gliders are deployed globally to gather oceanographic data from across the world's oceans. This thesis examines the utility of underwater gliders within the context of providing additional U.S. Navy capabilities. An extensive survey of available underwater gliders was undertaken and the resultant survey pool of ten gliders down selected to five gliders of fixed wing configuration. A comprehensive architectural analysis was then conducted of seven key architectural attributes of the five selected gliders. The architectural analysis compared various implementations of the key architectural attributes relative to desirable traits and capabilities for a notional U.S. Navy glider. Following the architectural analysis a proposed architecture for a U.S. Navy underwater glider was developed which includes a compendium of 'best' features gleaned from the architectural analysis. Drivers and rationale for selection of specific key architectural attributes and features are also provided. Additionally, a comparison of constraints and capabilities of underwater gliders is provided. Finally, a comparison of the current and proposed capabilities of underwater gliders versus other Autonomous Undersea Vehicles, specifically Unmanned Undersea Vehicles, is proffered.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	BACKGROUND	1
B.	PURPOSE.....	4
C.	RESEARCH QUESTIONS	4
D.	BENEFITS OF STUDY.....	5
E.	SCOPE AND METHODOLOGY.....	5
II.	SURVEY OF UNDERWATER GLIDERS IN THE COMMERCIAL MARKETPLACE.....	9
A.	INTRODUCTION.....	9
B.	SURVEY OF EXISTING COMMERCIALLY PRODUCED UNDERWATER GLIDER.....	9
C.	CHAPTER SUMMARY.....	19
III.	SELECTION OF GLIDER SYSTEMS, SIGNIFICANT GLIDER ARCHITECTURE ATTRIBUTES AND SYSTEM CONSIDERATIONS THAT INFLUENCE THESE ATTRIBUTES.....	21
A.	INTRODUCTION.....	21
B.	GLIDER SYSTEM SELECTION.....	21
	1. Spray.....	22
	2. ANT	23
	3. Slocum Electric.....	24
	4. Slocum Thermal.....	26
	5. Sea Glider	27
	6. eFolaga	29
	7. SeaExplorer.....	31
C.	ARCHITECTURAL FEATURES OF UNDERWATER GLIDERS.....	32
	1. Hull	32
	2. Buoyancy Mechanism	33
	3. Wings and Stabilizer Surfaces.....	35
	4. Control (pitch, yaw, roll).....	36
	5. Sensors Wetted and Non-wetted.....	37
	6. Communication/Navigation	38
	7. Launch and Recovery	38
D.	CHAPTER SUMMARY.....	41
IV.	RECOMMENDATION OF UNDERWATER GLIDER ARCHITECTURE FOR U.S. NAVY USE	43
A.	INTRODUCTION.....	43
B.	GLIDER ARCHITECTURAL RECOMMENDATION	43
	1. Hull	43
	2. Buoyancy Mechanism	44
	3. Wing and Stabilizer Surfaces.....	45
	4. Control (pitch, roll, yaw).....	46

5.	Sensors Wetted and Non-wetted	47
6.	Communications/Navigation	49
7.	Launch and Recovery	50
C.	CHAPTER SUMMARY	51
V.	OPERATIONAL CONSTRAINTS AND CAPABILITIES OF UNDERWATER GLIDERS	53
A.	INTRODUCTION	53
B.	GLIDER CONSTRAINTS	53
C.	GLIDER CAPABILITIES	56
D.	COMPARISON OF UNDERSEA GLIDERS AND OTHER AUVS IN TERMS OF OPERATIONAL CAPABILITIES AND CONSTRAINTS.....	58
E.	SUMMARY	59
VI.	SUMMARY AND CONCLUSIONS	61
A.	SUMMARY	61
B.	AREAS TO CONDUCT FURTHER RESEARCH	64
	LIST OF REFERENCES.....	67
	INITIAL DISTRIBUTION LIST	71

LIST OF FIGURES

Figure 1.	SLOCUM Glider Dive Profile, from (P. Simonetti, 1992).....	2
Figure 2.	Communication architecture among the Folaga, the control interface and the mission interface, from (Alvarez & et al, 2009)	3
Figure 3.	Underwater Glider #1 – Spray after (BlueFin Robotics, 2012a).....	10
Figure 4.	Glider #2 ANT – Littoral after (ANT-LLC, 2010).....	11
Figure 5.	Glider #3 - Slocum Electric after (Webb Research, 2012a)	12
Figure 6.	Glider #4 -Slocum Thermal after (Webb Research, 2012b).....	13
Figure 7.	Glider #6 - Sea Glider after (iRobot, 2012)	14
Figure 8.	Glider #7 - eFolaga after (Caffaz & et, 2010).....	15
Figure 9.	Glider #8 – SeaExplorer after (ASCA - ALCEN, 2012)	16
Figure 10.	Glider #9 - Petrel after (Wu & Wang, 2011)	17
Figure 11.	Glider #10 – Liberdade ZRay afer (ONR, 2012)	18
Figure 12.	Spray Glider (BlueFin Robotics, 2012a)	22
Figure 13.	Spray Internal Configuration from (Elvander & Halgleish, 2011)	23
Figure 14.	ANT Glider from (ANT-LLC, 2010)	24
Figure 15.	ANT Internal Configuration from (ANT-LLC, 2010).....	24
Figure 16.	Slocum Electric from (Webb Research, 2012a).....	25
Figure 17.	Slocum Electric Internal Configuration from (C. Jones, 2009).....	25
Figure 18.	Slocum Electric Internal Configuration from (PMEL Engineering Development, 2012)	26
Figure 19.	Slocum Thermal from (Webb Research, 2012b)	27
Figure 20.	Slocum Thermal Internal Configuration from (Carlowics & Lippsett, 2008)	27
Figure 21.	SeaGlider External/Internal Configuration from (University of Washington, 2012)	28
Figure 22.	SeaGlider (Deep) Internal Configuration from (Wood, 2009).....	29
Figure 23.	eFolaga from (Graal Tech 2011)	30
Figure 24.	Internal Configuration of Efolaga (Alvarez, et al 2009)	30
Figure 25.	SeaExplorer from (ASCA - ALCEN 2012)	31
Figure 26.	SeaExplorer Internal Configuration from (ASCA - ALCEN 2012)	32
Figure 27.	Spray Glider Launch w/Strap & Davit from (Krupski, 2012).....	39
Figure 28.	Spray Glider Launch Fixture from (WHOI, 2012).....	39
Figure 29.	Slocum Electric Launch from Surface Ship Guide Rails from (Quest Marine Services, 2007).....	40
Figure 30.	Potential Sensor Packages and Modular Payload Bay from (Jones, 2009)	48
Figure 31.	Potential Sensors and Suites from (Jones, 2009)	48

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	Recommended Architecture for U.S. Navy Underwater Glider	52
----------	--	----

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

A	Alkaline
ANT	Alaskan Native Technologies
ARGOS	Advanced Research and Global Observation Satellite
AUV	Autonomous Unmanned Vehicle
AUVAC	Autonomous Unmanned Vehicle Applications Center
ALACE	Autonomous Lagrangian Circulation Explorer
ATR	Automatic Target Recognition
CTD	Conductivity, Temperature and Depth
DDS	Dry Dock Shelter
GPRS	Global Packet Radio Service
GPS	Global Positioning System
GSM	Global System Mobile
INU	Inertial Navigation Unit
IP	Internet Protocol
L	Lithium
LAN	Local Area Network
LBS	Littoral Battle Space
LEWK	Loitering Electronic Warfare Killer
LLC	Limited Liability Corporation
LRIP	Low Rate Initial Production
MCM	Mine Counter Measure
NiMh	Nickel Metal Hydride
NPS	Naval Post Graduate School (Monterey, CA)

NOAA	National Oceanographic and Atmospheric Association
ONR	Office of Naval Research
REA	Rapid Environmental Assessment
REMUS	Remote Environmental Monitoring Unit System
RF	Radio Frequency
RIB	Rigged Inflatable Boat
SVP	Sound Velocity Profile
TCP	Transmission Control Protocol
UHF	Ultra High Frequency
UK	United Kingdom
U.S.	United States
USS	United States Ship
UUV	Unmanned Undersea Vehicle
WHOI	Woods Hole Oceanographic Institute

EXECUTIVE SUMMARY

This thesis examines the utility of underwater gliders within the context of providing additional U.S. Navy capabilities. A notional architecture for a U.S. Navy glider is proposed based on an extensive survey of available underwater gliders and a rigorous analysis of desirable key architectural attributes. The resultant, proposed, U.S. Navy underwater glider architecture includes: seawater compressibility matched composite hull, forward and aft wetted sections, two pump buoyancy system, aft swept fixed wings at 45 degrees, pitch control by buoyancy change and internal weight movement, yaw control by actuated vertical stabilizer (with embedded antenna), standard sensor suite of Conductivity/Temperature/Depth (CTD)/compass/altitude, separate sensor payload bay with fixed interfaces, structural features allowing launch/recovery from surface craft and submarine payload tubes.

With a notional architecture of the proposed U.S. Navy glider established, a comparison of constraints and capabilities of underwater gliders was undertaken. The limiting constraint is the need to intermittently surface to transmit data and receive tasking instructions. The dominant capability is the ability to maintain a persistent presence in a given operating area as a result of the underwater glider's significant endurance capability. Finally, a comparison of the current and proposed capabilities of underwater gliders versus other Autonomous Undersea Vehicles (AUV), specifically Unmanned Undersea Vehicles (UUVs), is conducted. This comparison results in the recommendation to use a fleet of underwater gliders as a U.S. coastal protection trip-wire system or as detection and tracking vehicles for locating threat patrol submarines.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to express my gratitude to Professor John Osmundson for providing his enthusiasm and promptness of review of my draft materials during this thesis effort and also to Mr. Steven Bousquet for freely volunteering to act as Second Reader.

Lastly I would like to thank my family for allowing me to pursue an advanced degree given our intensive schedule demands.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

Unmanned Autonomous Vehicles (AUVs) for the undersea domain have taken many forms in the past decades. AUV capability, and particularly autonomy, of these devices have increased significantly as AUV technology has evolved. AUV underwater devices range from simple data gathering devices to highly sophisticated Unmanned Undersea Vehicles (UUVs). An example of a data-gathering device is the SeaBird Electronics, ALACE (Autonomous Lagrangian Circulation Explorer) float (Seabird Inc., 16 Apr, 2012), which reports temperature, salinity and drift data from the world's oceans via satellite to the ARGOS (Advanced Research and Global Observation Satellite) satellite network. While an example of a highly sophisticated UUV is the Remote Environmental Measuring Unit (REMUS) (Kongsberg Maritime, 2012) used for debris field mapping, environmental monitoring and search and salvage operations.

Between the simple data gathering devices and highly sophisticated UUVs, exists a class of vehicle known as underwater gliders. Although many attribute the idea for underwater gliders to Henry Strommel from his fictional work (Strommel, 1989), underwater gliders were originally the vision of Douglas Webb, the founder of Webb Research, Falmouth, MA. The underwater glider concept was to conduct, controllable, mobile, measurements of conductivity, temperature and salinity in the world's oceans. This is in direct contrast to the ALACE floats, which inherently follow the path of the ocean's current. Underwater gliders function by changing buoyancy to move up and down vertically while fixed wings turn vertical motion into horizontal motion. A typical trajectory of an underwater glider is shown in Figure 1. The trajectory is 'saw-tooth' in nature as the glider repetitively descends and ascends the ocean environment.

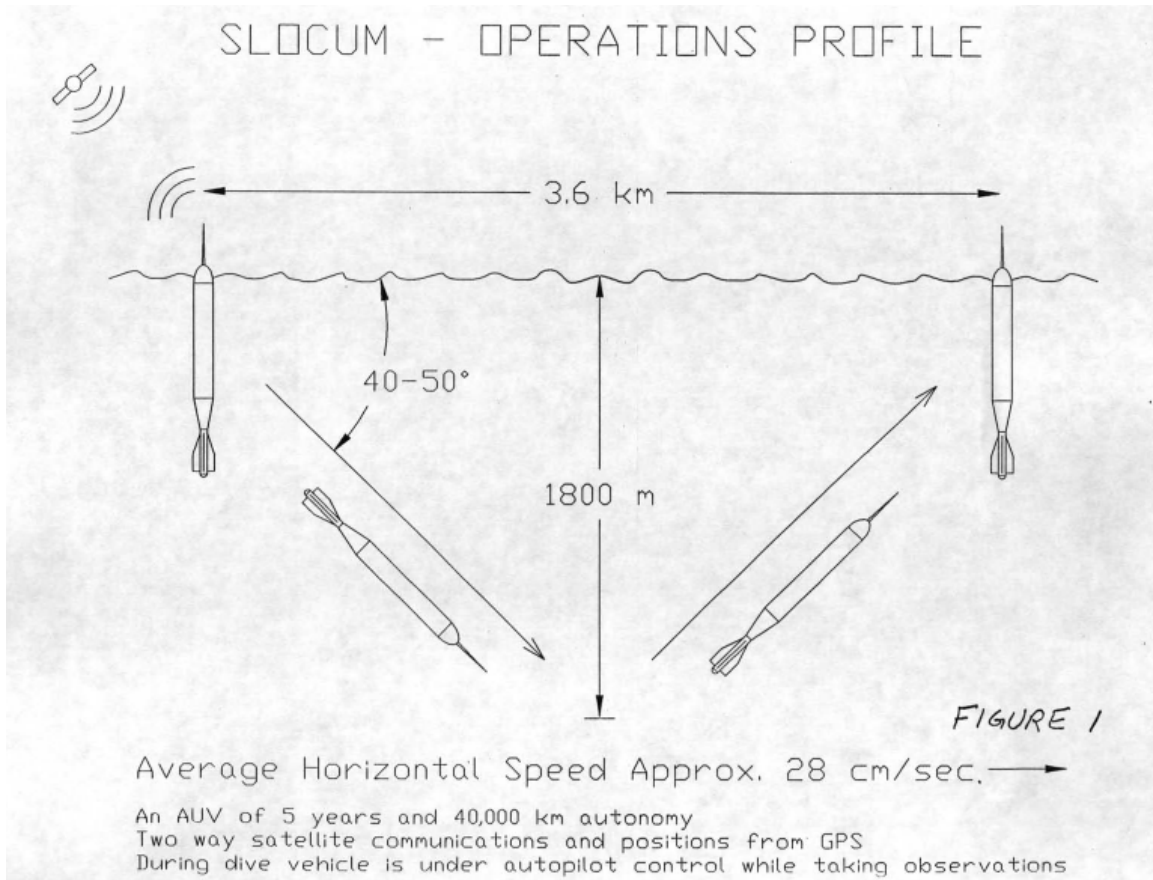


Figure 1. SLOCUM Glider Dive Profile, from (P. Simonetti, 1992)

During these saw-tooth evolutions, the vehicle's sensor and data acquisition systems are constantly taking and recording samples of the ocean's conductivity, temperature and depth. Every 6 hours the glider is programmed to surface so that data may be uploaded via a satellite (Iridium, ARGOS) and additional or modified commands downloaded to the glider to alter its planned location/glide path. This is exhibited schematically in Figure 2.

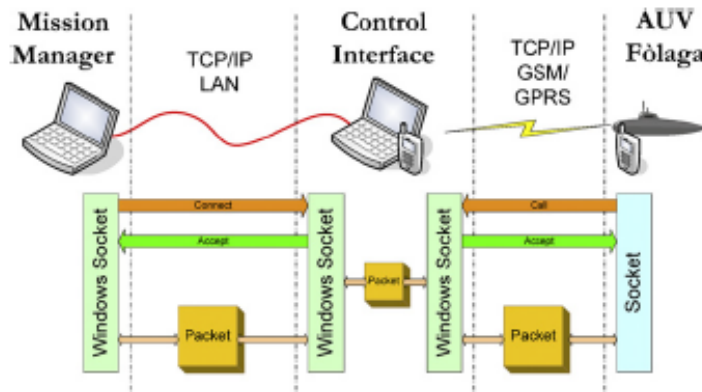


Figure 2. Communication architecture among the Fòlaga, the control interface and the mission interface, from (Alvarez & et al, 2009)

Although underwater gliders started as relatively simple vehicles, traversing the ocean's layers, they have become increasingly sophisticated and complex over the past decade. Today, a wide variety of underwater gliders exists, many with architectures and features similar to that of the original underwater glider, the Slocum (P. Simonetti, 1992). Although these gliders share, some similar architectural features there are differences in approaches to hull design (shape and compressibility), buoyancy mechanism (electrical, thermal, and other) and communication antenna placements and overall operation. This thesis seeks to understand these commonalities and differences and recommend the paramount underwater glider architectural features for the United States (U.S.) Navy's incorporation in its overall plan of battle.

Additionally, this thesis investigates the architectural features dominating the design of underwater gliders and how these dominant features influence the overall underwater glider design. Additionally, these overall architectures and dominant features will be analyzed to determine their impacts on the ability of underwater gliders to be launched and recovered from existing U.S. Navy platforms (surface and submarine).

Furthermore, the operational constraints and capabilities of undersea gliders will be examined relative to the requirements delineated in the U.S. Navy's UUV Master Plan (U.S. Navy, 2004). This will allow determination of

undersea glider effectiveness in filling existing gaps in the UUV master plan or if other AUVs such as UUVs would, more effectively fill these gaps. Specifically, the goals from the 2004 UUV Master (U.S. Navy, 2004) plan are:

1. Intelligence, Surveillance, and Reconnaissance
2. Mine Countermeasures
3. Anti-Submarine Warfare
4. Inspection / Identification
5. Oceanography
6. Communication / Navigation Network Node
7. Payload Delivery
8. Information Operations
9. Time Critical Strike

B. PURPOSE

The purpose of this study is to analyze the different systems architectures utilized in today's commercially available underwater gliders. Various attributes of the commercially available underwater gliders will be investigated, including hull design and shape, buoyancy mechanism and communications implementation. The utility of underwater gliders in the U.S. military's UUV Master Plan will also be evaluated as well as underwater glider constraints and capabilities relative to UUVs.

C. RESEARCH QUESTIONS

This thesis will analyze the existing commercially available undersea glider architectures and based on analysis of specific, desirable attributes, propose an undersea glider architecture for United States (U.S.) Navy applications. The proposed undersea glider architecture will be examined for prospective integration onto U.S. Navy surface and submerged combatants. Additionally, the capabilities and constraints of undersea gliders will be discussed and contrasted to other types of Autonomous Undersea Vehicles (AUVs),

specifically Unmanned Undersea Vehicles (UUVs). The specific research questions are:

- What are the prevalent architectural features of currently existing commercial undersea gliders?
- How is undersea glider design driven by prevalent architectural features of currently existing commercial undersea gliders?
- What are the paramount architectural features for a U.S. Navy undersea glider?
- What are the operational constraints of undersea gliders?
- What are the operational capabilities of undersea gliders?
- How do undersea gliders compare to other types of AUVs in terms of operational capabilities and operational constraints?

D. BENEFITS OF STUDY

A result of this thesis will be determination of architectural characteristics prevalent to the design of undersea gliders. Based on determination of these architectural characteristics a conglomerate design is proposed complimentary to launch and recovery requirements from U.S. Navy platforms. This study will also aid the U.S. Navy in its assessment of underwater glider's utility and capability relative to the Navy's UUV Master Plan. In particular, evaluations of military capabilities and constraints of underwater gliders are compared to those of existing commercial UUVs.

E. SCOPE AND METHODOLOGY

This study seeks to determine the pertinent architectural design parameters for development of a proposed U.S. Navy underwater glider. A literature search of all commercially available underwater gliders is therefore conducted. This literature search focuses solely on commercially available, buoyancy driven, underwater gliders. Hybrid underwater gliders (buoyancy and electrically propelled combined) are not included. However, design features of

hybrids relevant to the current thesis will be evaluated as appropriate (i.e. hull design/communications implementation).

Next, a systematic system engineering approach is utilized to determine those architectural parameters which complement both the U.S. Navy's UUV Master Plan and its launch and recovery of underwater gliders from current U.S. Navy fleet assets. Finally, there is discussion of the capabilities and constraints of underwater gliders in direct comparison to commercially available UUVs.

The overall methodology of this thesis is provided below and the accompanying sections which follow are aligned in similar fashion.

1. Conduct a comprehensive literature search on currently available underwater gliders and their architectural traits.
2. Dependent on the number of underwater gliders commercially available conduct a down selection, to limit the total number of unique underwater gliders examined.
3. Examine the architectural features of the down selected underwater gliders. Compile a listing of architectural traits which have a significant impact on the overall systems engineering approach to design of the underwater gliders. Down select to those architectural features relevant to potential U.S. Navy implementation of underwater gliders in the order of battle.
4. Based on the results of item (3) above propose a glider configuration which potentially shores-up shortfalls in the current UUV Master Plan and enables launch and recovery of underwater gliders from existing U.S. Navy platforms (surface and submarine).
5. Review the constraints imposed on underwater gliders by their intrinsic design features relative to potential maritime naval missions.

6. Evaluate the military capabilities of underwater gliders relative to those of existing UUVs and the UUV Master Plan.

The next chapter contains a comprehensive survey of commercially available underwater gliders both in the United States and abroad.

THIS PAGE INTENTIONALLY LEFT BLANK

II. SURVEY OF UNDERWATER GLIDERS IN THE COMMERCIAL MARKETPLACE

A. INTRODUCTION

This chapter presents a comprehensive survey of underwater gliders currently available in the commercial marketplace, both in the U.S. and abroad. The overall scope of this survey includes gliders which alter operational depth via pure buoyancy means only and also hybrid gliders that alter depth via a combination of buoyancy and propulsive means. The underwater glider survey which follows was conducted purely from open source research materials available to the public and considers only those underwater gliders that are currently commercially available or thought near Low Rate Initial Production (LRIP). Prototypes, university or governmental research and developmental units were not included, as these are typically one of a kind units not meant for eventual commercial production. In the following chapter, the resultant population of commercial underwater gliders is examined for prevalent architectural features relevant to potential U.S. Navy military usage.

B. SURVEY OF EXISTING COMMERCIALY PRODUCED UNDERWATER GLIDER.

As a first cut, at determining the extent of underwater gliders available, the online Autonomous Undersea Vehicle Applications Center (AUVAC) database was consulted. Additionally, numerous vendor websites and the Naval Post Graduate School BOSUN library were queried. The results are shown in common quad charts format shown in Figures 3 thru 11. Note that this particular quad chart format was derived from reference (French, 2010). Therefore, “the four quadrants consist of applications, features, energy/endurance/propulsion and payload/sensors” (French, 2010). The quad charts highlight the main architectural and capability differences between the available gliders. Note that many variations of these gliders exist, i.e., built on a Slocum or Seaglider platform. Therefore, to avoid repetitive configurations of Slocum or Seaglider

vehicles within the subject survey, which were modified for particular purposes, but retain the same base architecture, only the base configurations were included in the survey findings.

Spray Glider Country of Origin: U.S. Provider: Bluefin Robotics Source: www.bluefinrobotics.com	
 Applications • Oceanography • Environmental Protection & Monitoring • Scientific Research Launch & Recovery • Man Portable (2 people)	 Features • Length: 213 cm • Diameter: 20 cm • Wing Span: 110 cm • Dry/Air Weight: 52 kg • Buoyancy: 0.4 kg (net positive) • Volume Change: 700 cc • Depth Rating: 1500 m • Construction: 3 Piece 6061-T6 • Comms – GPS/Iridium both wings, Argos integrated in tail
Buoyancy, Energy, Endurance, Control • Buoyancy System: Hydraulic Pump • Energy System: 17.5 MJ Lithium Primary • Range/Endurance: 4800 km/6 months • Speed: 0.2 m/sec • Pitch/Roll: Battery Pack Motion	Payload & Sensors • Conductivity/Temperature/Depth • Dissolved Oxygen (optional) • Fluorometer (optional) • Turbidity (optional) • Altimeter (optional)

Figure 3. Underwater Glider #1 – Spray after (BlueFin Robotics, 2012a)

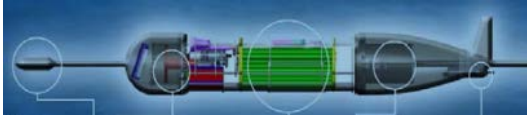
ANT Littoral (Deep Ocean)	
Country of Origin: US Provider: ANT, LLC Source: www.ant-llc.net	
 Applications • Intelligence, Surveillance, Reconnaissance • Anti-Submarine Warfare • Mine Countermeasure • Homeland Defense • Oceanography Launch & Recovery • Crane/Davit	 Features • Length: 2.0 m • Diameter: 32.4 cm • Wing Span: • Dry/Air Weight: 120 kg • Buoyancy: • Volume Change: • Depth Rating: 10 - 200 m (10-1,000 m) • Construction: 3 Section Aluminum • Comms: Iridium, Freewave UHF (Line of Sight), 802.11G LAN, GPS, Globalstar
Energy, Endurance, Propulsion Buoyancy System: Hydraulic Pump (dynamic 10-37 ppt) Energy System: Lithium Primary Pitch/Roll: Battery Pack Motion Range/Endurance: 185 km/30 days (1-yr) Speed: 1.0 m/sec (0.25-0.5 m/sec)	Payload & Sensors • Acoustic Altimeter • Omni-Directional Acoustic • Sound/Velocity/Temperature/Pressure • Directional Acoustic • 5kg Payload bay

Figure 4. Glider #2 ANT – Littoral after (ANT-LLC, 2010)

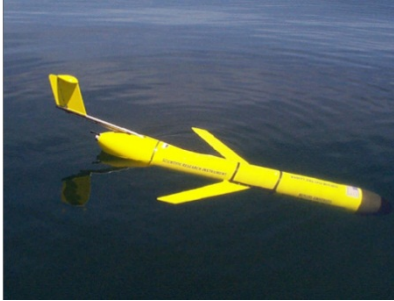
Slocum Electric Glider Coastal (Ocean) Country of Origin: US Provider: Teledyne Webb Research Source: www.webbresearch.com	
 Applications • Oceanographic Survey • Environmental Monitoring • Scientific Research • Rapid Environmental Assessment Launch & Recovery • Man Portable (1-2 people)	 Features • Length: 1.5 m • Diameter: 21.3 cm • Wing Span: 120 cm • Dry/Air Weight: 52 kg • Buoyancy: • Volume Change: • Depth Rating: 4 - 200 m (40-1000m) • Nose Section Dependent • Construction: 3-Section, Aluminum • Comms: RF Modem, Iridium, ARGOS, Telesonar Modem
Energy, Endurance, Propulsion Buoyancy System: Hydraulic Pump Energy System: Alkaline (A) or Lithium (L) • Pitch/Roll: Battery Pack movement • Yaw: Rudder Range/Endurance: 1500 km /50 days (A) 6000km/8 months (L) Speed: 0.4 m/sec	Payload & Sensors • Conductivity, Temperature, Depth • Acoustic Doppler Current Profiler • Oxygen • Hydrophones • Extendable Payload by for Sensors or Additional Energy Requirements

Figure 5. Glider #3 - Slocum Electric after (Webb Research, 2012a)

Slocum Thermal Glider Country of Origin: US Provider: Teledyne Webb Research Source: www.webbresearch.com	
 Applications • Oceanographic Survey • Environmental Monitoring • Scientific Research Launch & Recovery • Man Portable (1-2 people)	 Features • Length: 1.5 m • Diameter: 21.3 cm (main body) • Wing Span: 120 cm • Dry/Air Weight: 60 kg • Buoyancy: • Volume Change: • Depth Rating: 1200 m • Construction: 3-Section, Aluminum • Comms: RF Modem, Iridium, ARGOS,
Energy, Endurance, Propulsion Buoyancy System: Thermal Pump Energy System: Environmental • Pitch/Roll: Battery Pack movement • Yaw: Rudder Range/Endurance: 40,000 km/3-5 years Speed: 0.4 m/sec	Payload & Sensors • Conductivity, Temperature, Depth

Figure 6. Glider #4 -Slocum Thermal after (Webb Research, 2012b)

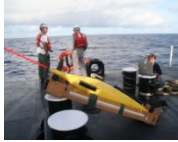
Sea Glider (Deep Glider)	
Country of Origin: US	Provider: iRobot Source: www.irobot.com
 Applications • Oceanographic • Surveillance • Reconnaissance • Harbor Defense Launch & Recovery • Man Portable (1-2 people)	 Features • Length: 1.8-2.0 m for trailing antenna add 0.43 or 1 m • Diameter: 30 cm (body max.) • Wing Span: 1 m • Dry/Air Weight: 52 kg • Buoyancy: • Volume Change: • Depth Rating: 20-1000 m • Construction: 3-Section, Isopycnal • Comms: Iridium, ARGOS,
Energy, Endurance, Propulsion Buoyancy System: Hydraulic Pump • Dual Pump 120-1000m • Single Pump 20-120 m Energy System: 10 MJ Lithium Sulfuryl Chloride • Pitch/Roll: Battery Pack movement Range/Endurance: 4,600 km/10 months Speed: 0.25 m/sec	Payload & Sensors • Altimeter • Acoustic Transponder • Conductivity Temperature Depth (CTD) • Backscatter/Fluorometer • Dissolved Oxygen • Photo-synthetically Active Radiation

Figure 7. Glider #6 - Sea Glider after (iRobot, 2012)

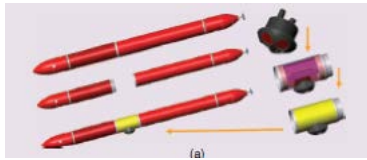
eFolaga		
Country of Origin: Italy	Provider: GRAAL	Source: www.graaltech.com
 Applications • Oceanographic Survey • Bottom Mapping • Marine Mammal Survey • Inspection and Security • Environmental Monitoring Launch & Recovery • Man Portable (1-2 people)	 Features • Length: 2.2 m • Diameter: 15.5 cm • Wing Span: none • Dry/Air Weight: 31 kg • Buoyancy: • Volume Change: • Depth Rating: 0-50 m • Construction: 3 section, graphite reinforced plastic forward/payload/aft • Comms: GPS, General Service Mobile Radio Service, Acoustic Modem	
Energy, Endurance, Propulsion Buoyancy System: Hydraulic Pump Propulsion System: Jet Pump/Propeller Pitch/Roll/Yaw: Hydro-jet/movable ballast Energy System: 12 V, 45 Ah NiMh Range/Endurance: unknown/6 hours Speed: 1.01 m/sec (jet), 2.02 m/sec (prop)	Payload & Sensors • Conductivity, Temperature • Optical Sensor • Towed Array • Sidescan Sonar • General Payload Module	

Figure 8. Glider #7 - eFolaga after (Caffaz & et, 2010)

SeaExplorer Country of Origin: France Provider: Alcen Source: www.asca-alcen.com	
 Applications • Oceanography & Science • Pollution Detection • Water Quality Monitoring • Rapid Environment Assessment • Marine Mammals Assessment Launch & Recovery • Man Portable (2-people)	Features • Length: 2.2 m antenna 0.7m folds • Diameter: 25 cm • Wing Span: none • Dry/Air Weight: 59 kg • Buoyancy: • Volume Change: 1 liter • Depth Rating: 700 m • Construction: 6 section, (unknown) • Comms: Iridium, Acoustic, Local Radio
Energy, Endurance, Propulsion Buoyancy System: Hydraulic Pump Yaw/Roll: Vertical/Horizontal Stabilizers Energy System: Lithium Range/Endurance: unknown (payload dependent) Speed: 0.5 m/sec	Payload & Sensors • Conductivity, Temperature • Dissolved Oxygen • Scattering • Fluorescence • General Payload Modules (5kg in 2 modules)

Figure 9. Glider #8 – SeaExplorer after (ASCA - ALCEN, 2012)

Petrel Country of Origin: China Provider: Tianjin University Source: auvac.org/publications/view/184	
 Applications • Marine Survey • Environmental Monitoring Launch & Recovery • Davit Crane	 Features • Length: 3.2 m • Diameter: 25.0 cm • Wing Span: 1.8 m • Displacement: 130 kg • Buoyancy: • Volume Change: 1400 ml • Depth Rating: 0-50 m • Construction: 4 section, • Comms: GPS, wireless
Energy, Endurance, Propulsion Buoyancy System: Hydraulic Pump Propulsion System: Propeller Pitch/Roll System: Battery Pack Motion (glide mode) Pitch/Yaw System: Horizontal/Vertical Rudder (thrust mode) Energy System: Range/Endurance: Speed: 0.5 m/sec (glide), 2.0 m/sec (thrust)	Payload & Sensors • Conductivity, Temperature

Figure 10. Glider #9 - Petrel after (Wu & Wang, 2011)

Liberdade ZRay Country of Origin: US Provider: Scripps Institute Source: www.onr.navy.mil	
 Applications • Mammal Tracking • Track Diesel Electric & Fuel Cell Submarines Launch & Recovery • Specially Designed L&R Platform	Features • Length: • Wing Span: 6.1 m • Dry Weight: 1500 lb • Buoyancy: • Volume Change: • Depth Rating: 300 m • Construction: ABS over Ti frame • Comms: Underwater Acoustic Modem, Iridium Satellite
Energy, Endurance, Propulsion Buoyancy System: Propulsion System: Pitch/Roll System: Pitch/Yaw System: Energy System: Range/Endurance: 1200-1500 km Speed: 1-3 kts	Payload & Sensors • Hydrophone Array(s) - o Leading Edge - o Trailing Edge

Figure 11. Glider #10 – Liberdade ZRay afer (ONR, 2012)

Additionally, as stealth is of major importance for tactical underwater gliders, those vehicles with portions, which normally reside on the ocean surface were not considered. (An example of this is the WaveGlider, from Liquid Robotics (Liquid Robotics, 2012), which utilizes wave motion to provide the forward/downward and upward cyclic motion for its submerged vehicle which is in turn tethered to a surf-board like vehicle on the ocean surface.)

Furthermore, complete data was not available, or proprietary, for all of the gliders contained in the survey. Accordingly, the quad charts may exhibit blank data fields where information was unavailable from open sources.

C. CHAPTER SUMMARY

This chapter presented a survey of the available underwater gliders from within the U.S. and abroad. Both proper buoyancy driven and hybrid buoyancy/propulsive gliders were considered in this survey. Those gliders used by academia, commercial and military prototypes were not considered as they have not reached even low initial rate of production (LRIP) quantities. There exists a limited number of underwater gliders with complete characterization information available in open literature. Therefore, only those gliders with complete characterization information available were carried into the study on underwater glider system architectural features relevant to a U.S. Navy underwater glider discussed in the following chapter.

THIS PAGE INTENTIONALLY LEFT BLANK

III. SELECTION OF GLIDER SYSTEMS, SIGNIFICANT GLIDER ARCHITECTURE ATTRIBUTES AND SYSTEM CONSIDERATIONS THAT INFLUENCE THESE ATTRIBUTES

A. INTRODUCTION

This chapter down selects from the underwater gliders surveyed in the previous chapter in order to provide a comparison of the associated significant architectural attributes. Although the underwater glider survey resulted in a compilation of conventional (buoyancy only), hybrid gliders (buoyancy and propulsion) and flying wing gliders only conventional and hybrid gliders are considered in the following architectural attribute discussion. This is necessary to restrain the scope of the resultant architectural attribute discussion. Additionally, the conventional and hybrid gliders selected have significantly more at-sea time and higher current or near-term rates of production than the flying wing glider (Liberdade Zray). Note, one hybrid glider, Petrel, had insufficient open source information available regarding internal arrangement of components or its operation. Therefore, this glider was eliminated from the study that follows and should be reconsidered once more open source information becomes available.

B. GLIDER SYSTEM SELECTION

For this effort, seven underwater gliders were deemed either commercial successes or had significant potential for near term viable commercial successes. The determination of current commercial or near term viable commercial success was based on four traits: number of units sold, number of similar prototypes successfully at-sea tested or demonstrated, manufacturer/distributor training availability and at-sea time. The section, which follows, delineates the basic information of each glider and consists of identification of the manufacturer, key features of the glider and external and cross-sectional view of the associated glider. The gliders are presented in the following order:

- Spray
- ANT
- Slocum Electric
- Slocum Thermal
- Sea Glider
- eFolaga
- SeaExplorer

1. Spray

Bluefin Robotics, Quincy, MA under license from the Scripps Institution of Oceanography, manufactures the Spray glider. The Spray technology has been licensed by Bluefin since 2004 although it has been modified since that initial licensing (BlueFin Robotics, 2012b). According to Bluefin Robotics (BlueFin Robotics, 2012b) *“The Bluefin Spray Glider is a deep-diving, buoyancy-driven autonomous underwater vehicle. The Spray collects water column data profiles using a pumped, conductivity-temperature-depth (CTD) sensor and other instruments. Deployments of up to 6 months can be achieved with a single set of batteries”*. The Spray glider is shown in Figures 12 and 13 in full and sectional views.



Figure 12. Spray Glider (BlueFin Robotics, 2012a)

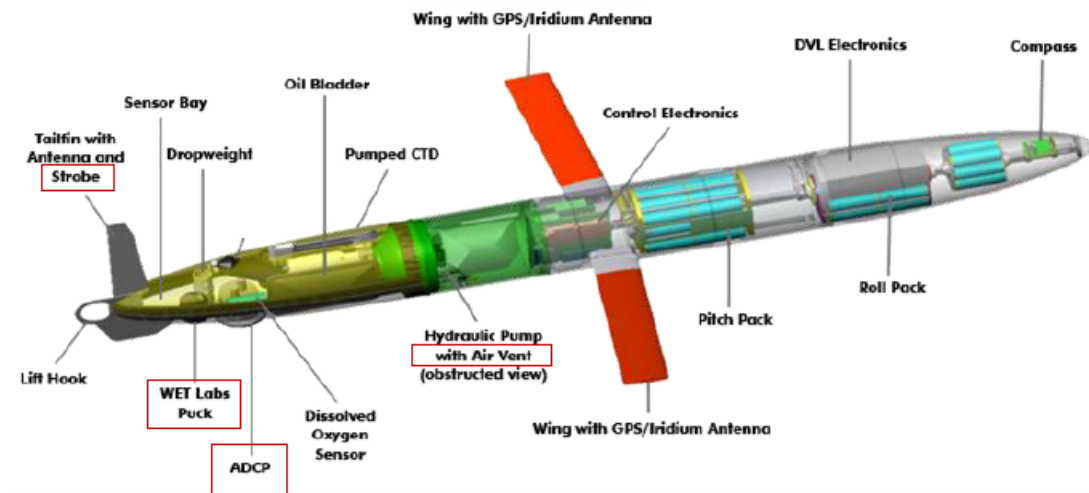


Figure 13. Spray Internal Configuration from (Elvander & Halgleish, 2011)

2. ANT

The ANT underwater glider is manufactured by ANT, LLC (formerly Alaskan Native Technologies) in Anchorage, AK. ANT was developed under sponsorship of the Office of Naval Research (ONR) and designed to meet the requirements of the US Navy Undersea Master Plan. Per the ANT, LLC website:

ANT has delivered 18 gliders to the US Navy and has enhanced the capabilities of the gliders by improving sensor sensitivity and adding mine detection, acoustic temperature profiling, object avoidance and swimmer detection to the already long list of glider capabilities.(ANT-LLC, 2010)

There have also been vague references in the media about ANT technology being licensed to the United Kingdom (UK) for its undersea applications. The ANT glider is shown in Figures 14 and 15 in full and sectional views.

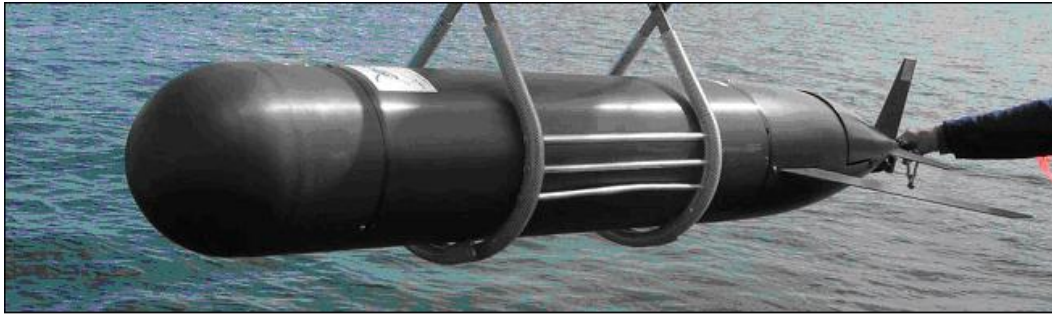


Figure 14. ANT Glider from (ANT-LLC, 2010)

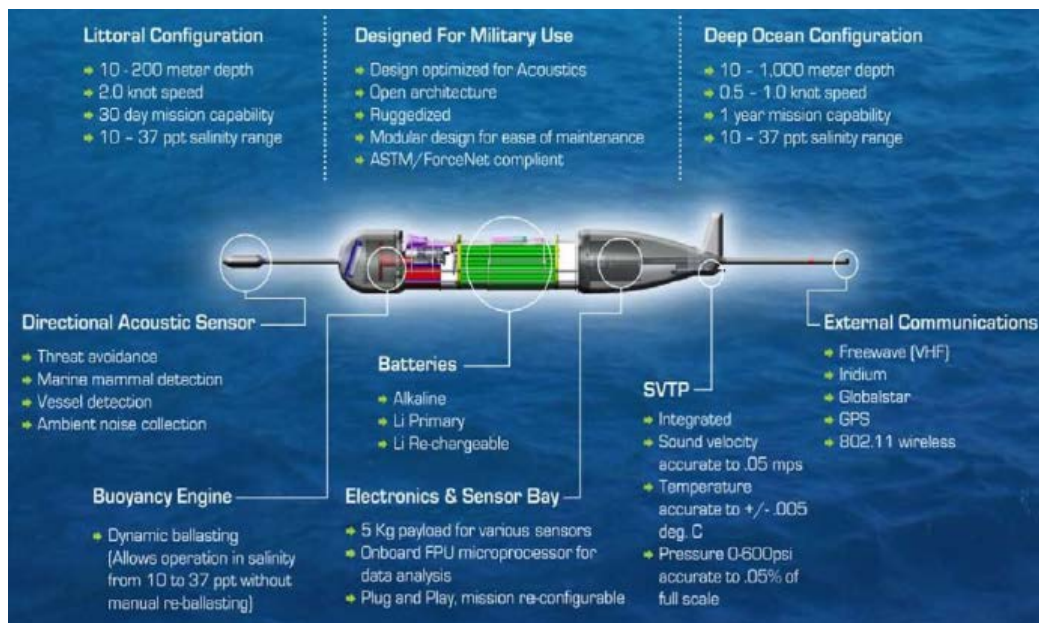


Figure 15. ANT Internal Configuration from (ANT-LLC, 2010)

3. Slocum Electric

The Slocum Electric is manufactured by Teledyne Webb Research, East Falmouth, MA. The Slocum Electric utilizes electrically powered (battery) pumps to inflate/deflate external bladders to alter the overall buoyancy of the glider. Slocum Electric is manufactured in vary depth ratings 30m, 100m, and 200m. Additionally, there are also the G2 variant with modular pumps and the 1200m (aka Deep Electric) (Elvander & Halgleish, 2011). To date there have been numerous purchases of Slocum Electrics by various organization. These units

have been customized by these organizations for specific mission and sensor requirements. The auvac.org website listed 15 variations of the Slocum Electric being utilized by a number of both academic and commercial institutions.

Teledyne Webb Research has been awarded the Littoral Battlespace Sensing Glider contract from the U.S. Navy and has reached the first production milestone by delivering 15 Low initial Rate Production Units to the U.S. Navy (Webb Research, 2011) . From the open source literature, it is unclear which specific variant of Slocum is being utilized. However, initial prototypes appear to be of the Electric variant. The Slocum Electric glider is shown in Figures 16, and 17 and 18 in full and sectional views, respectively.



Figure 16. Slocum Electric from (Webb Research, 2012a)

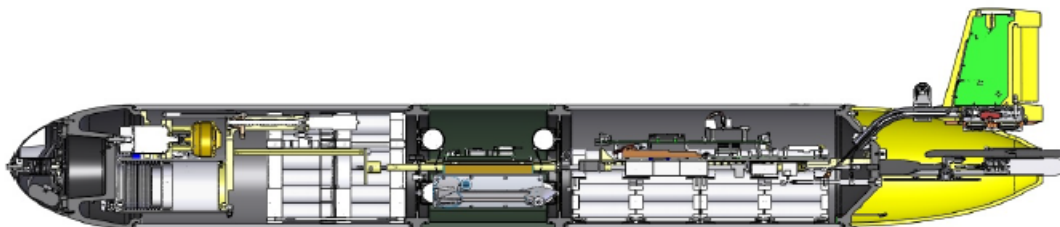


Figure 17. Slocum Electric Internal Configuration from (C. Jones, 2009)

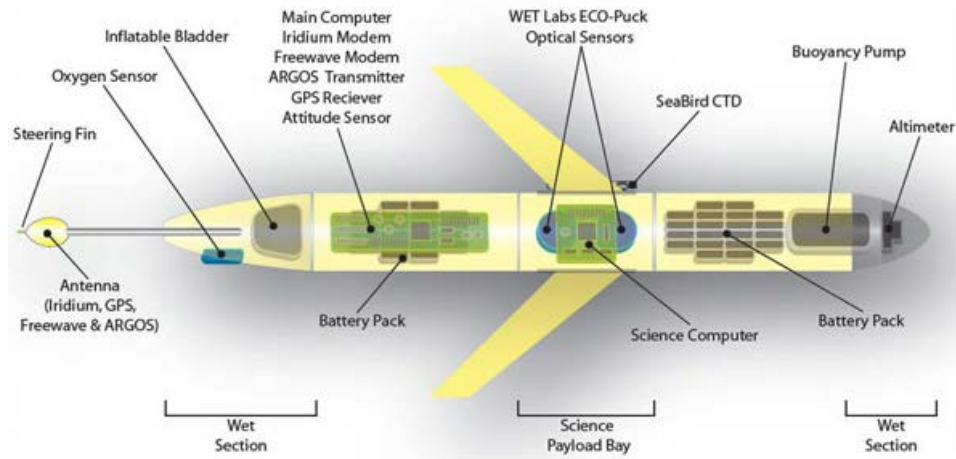


Figure 18. Slocum Electric Internal Configuration from (PMEL Engineering Development, 2012)

4. Slocum Thermal

Similar to the Slocum Electric, the Slocum Thermal is manufactured by Teledyne Webb Research, East Falmouth, MA. The Slocum Thermal has a depth rating of 1200m. The significant difference between the Thermal and Electric versions of the Slocum is in the buoyancy/propulsion mechanism. The Thermal variant uses changes of state in wax (discussed later) to alter the buoyancy of the glider and operates in areas with a minimum of 10 degrees F difference in water temperature. No electric power is utilized for buoyancy changes. The Slocum Thermal glider is shown in Figures 19 and 20 in full and sectional views, respectively.



Figure 19. Slocum Thermal from (Webb Research, 2012b)

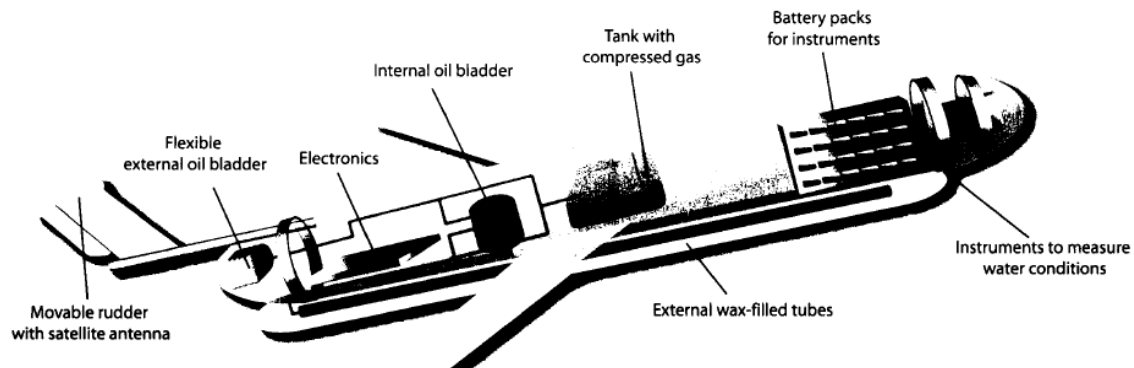


Figure 20. Slocum Thermal Internal Configuration from (Carlowics & Lippsett, 2008)

5. Sea Glider

Sea Glider is manufactured by iRobot, Bedford, MA based on work conducted at the University of Washington, Applied Physics Laboratory, Seattle, WA. The Sea Glider has a maximum depth of approximately 1000m. There are two variants of Sea Glider. A two pump variant for depths between 120 and 1000 m and a single pump variant for depths from surface to 120 m. The single

pump variant uses less energy than the two pump variant thus increasing the overall mission duration via battery life increase (iRobot, 2012). Additionally, the two pump variant consists of a booster pump and a main pump. The booster pump provides higher inlet pressure to the main pump thus reducing overall electrical consumption over a single pump without booster. The Sea Glider is shown in Figures 21 and 22 in full and sectional views, respectively.

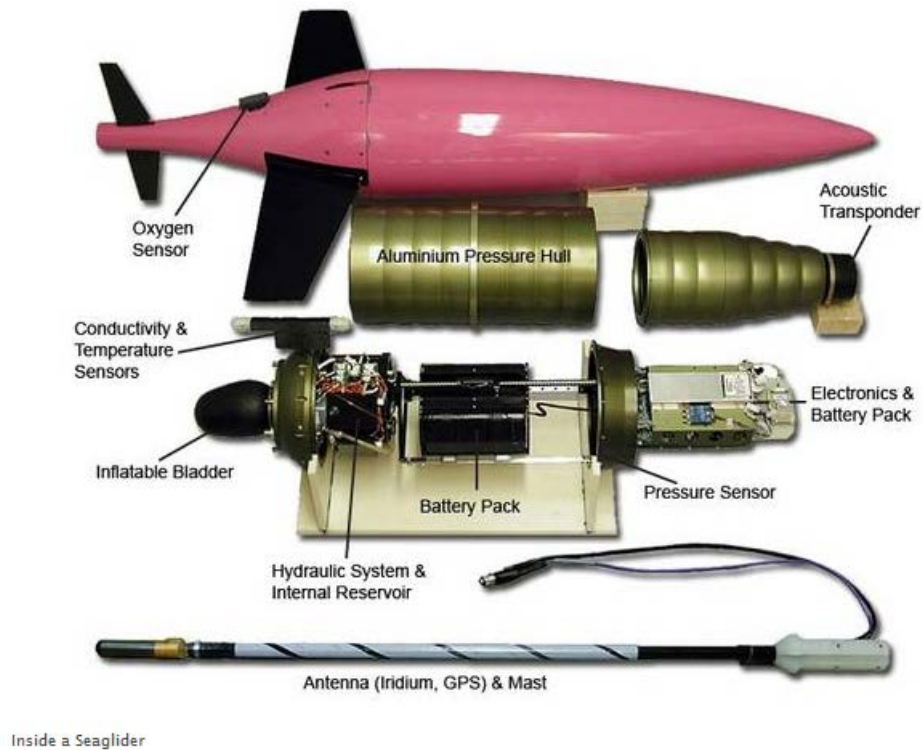


Figure 21. SeaGlider External/Internal Configuration from (University of Washington, 2012)

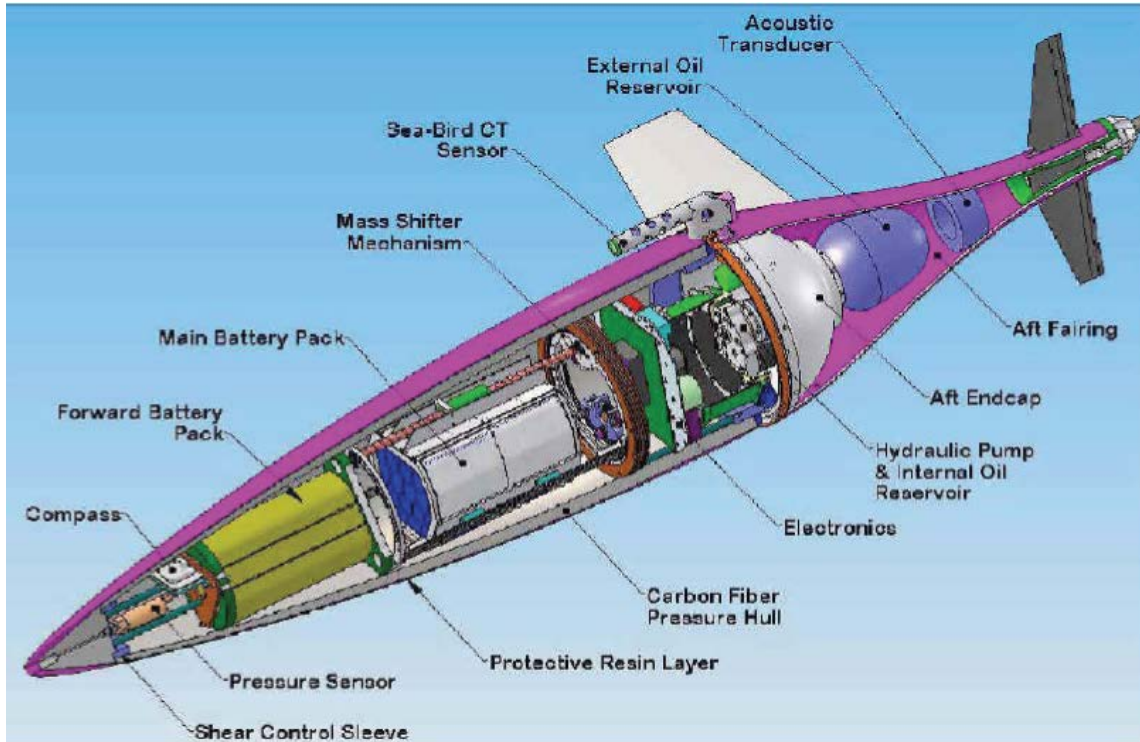


Figure 22. SeaGlider (Deep) Internal Configuration from (Wood, 2009)

6. eFolaga

The eFolaga hybrid underwater glider is manufactured by GRAAL Tech of Genova, Italy. The eFolaga underwater glider is one of a few hybrid gliders which utilize the buoyancy change mechanisms of typical underwater gliders but eliminate the wings required for generating lift and subsequent forward motion. In place of lifting surfaces, forward thrust, yaw and pitch correction are generated by electrically powered thru hull thrusters imbedded in the vehicle. There is no roll control as the vehicle is designed to be roll neutral and without mid-body wings there is no roll required to generate turning forces. Figure 23 shows an external view of eFolaga while Figure 24 provide a schematic cutaway of the vehicle.



Figure 23. eFolaga from (Graal Tech 2011)

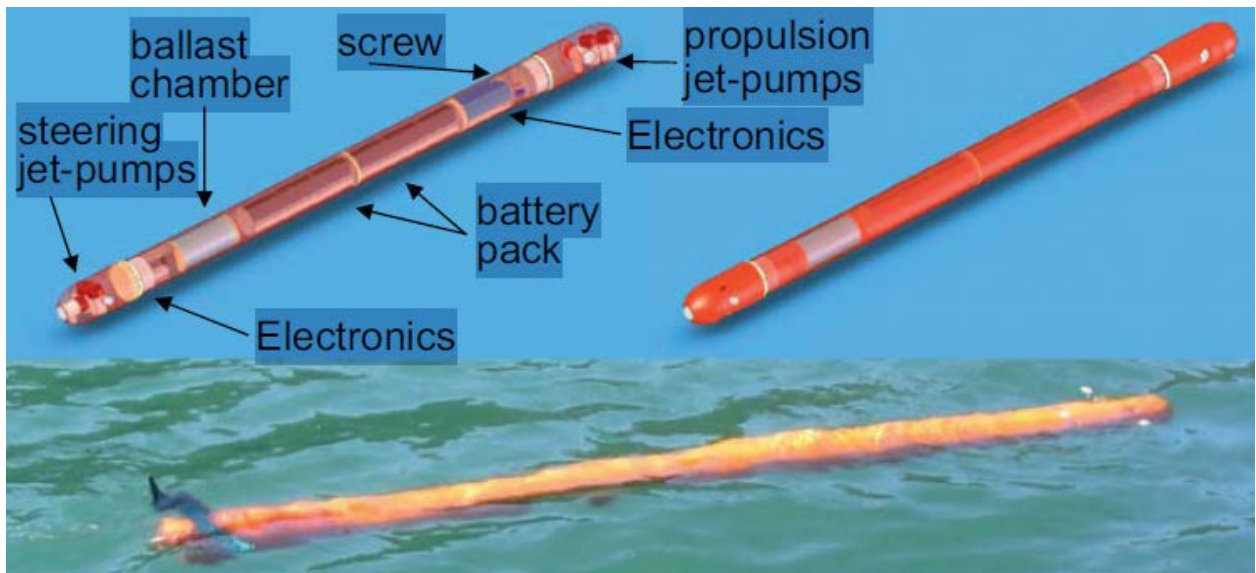


Figure 24. Internal Configuration of Efolaga (Alvarez, et al 2009)

7. SeaExplorer

The SeaExplorer underwater glider is produced by ASCA-Alcen, Mevreuil, France. The configuration of SeaExplorer removes the large wing-like surfaces prevalent on Spray, ANT, Slocum, and SeaGlider underwater gliders and replaces them with horizontal finned appendages on the vehicle afterbody. No additional jet pump or thrusters are utilized on SeaExplorer. An external view of SeaExplorer is provided in Figure 25.



Figure 25. SeaExplorer from (ASCA - ALCEN 2012)

An internal configuration view of SeaExplorer is shown in Figure 26. Sea Explorer is comprised of the five sections listed below (plus trailing antenna). From forward to aft the sections are:

- Wet payload
- Dry payload plus related electronics
- Batteries and actuators for weight movement



Figure 26. SeaExplorer Internal Configuration from (ASCA - ALCEN 2012)

- Ballast unit and navigation electronics
- Wet section- connectors and bladders

C. ARCHITECTURAL FEATURES OF UNDERWATER GLIDERS

1. Hull

The hull is the major structural component of underwater gliders. The pressure hull provides the seawater volume displacement to achieve the upward buoyant force to oppose the weight in air of the glider (in concert with lift from the wing surfaces or pump jets). The pressure hull provides a location for the pumping mechanism, batteries and electronics for control/sensor operation and pump jets if so equipped.

In contrast, the non-pressure hull provides the hydrodynamic fairness structure to reduce drag on the glider due to skin and frontal areas. Additionally,

the non-pressure hull provides wetted locations for the ballast bladder for buoyancy increase/decrease, and various sensors requiring a wetted location, such as wetted CTD.

The tradeoff with hull materials is between metals such as 6061-T6 aluminum and composite materials. At deeper depths the overall displacement of the vehicle is insufficient to overcome the increased weight due to wall thickness increases. Therefore, the use of composites becomes necessary due to their increased strength to weight ratios. However, the structural predication tools necessary to predict the performance of composites under explosive or shock loading is still in its exploratory development stage. Therefore, for all but submerged launch from submarines, composites hulls are appropriate.

Underwater glider hull designs are of two variations; compensated and uncompensated. A compensating hull has a compressibility equal to that of seawater and therefore changes in buoyancy are minimal. Non-compensating hulls have a compressibility less than that of seawater and therefore it is necessary to pump additional fluid from the interior of the pressure hull to the external bladder within the non-pressure hull.

Another function of the hull is the reduction of hydrodynamic drag. The amount of drag reduction required is dependent on the overall requirement on mission duration. From Figures 9 and 10 it is obvious that the relatively sharp leading edge on SeaGlider is meant to reduce overall hydrodynamic drag by maintaining laminar flow as long as possible and results in significant mission endurance increases.

2. Buoyancy Mechanism

There are two primary buoyancy mechanisms used in underwater gliders. These are electrical, or pumped, (Spray, ANT, Slocum Electric, SeaGlider, eFolaga and SeaExplorer) and thermal (Slocum Thermal).

The electrical (pumped) variant works by use of a bladder external to the pressure hull but within the fairing which is either filled with or purged of fluid (water or oil) taken from inside the pressure hull. Filling the bladder with fluid increases the buoyancy of the glider resulting in an upward motion. The upward motion is translated to a forward motion due to the lifting forces caused by flow over the wing surfaces. (Alternately, for gliders without wings, for example eFolaga, jet pump thrusters initiate the forward motion). Similarly a downward motion is initiated by pumping fluid out of the bladder thus reducing the gliders overall buoyancy.

The thermal variant works via a state change of a wax-like substance. As described on the AUVAC website:

The thermal engine consists of a heat exchange tube, accumulator, valve manifold, and both external and internal (to the pressure hull) bladders. The heat exchange tube is comprised of an outer aluminum pressure vessel that is filled with a wax chemistry tuned to undergo a phase change at 10 C. In the center of the wax is a flexible hose which can be filled with mineral oil. In operation, the glider leaves the surface by rotating the valve and allowing oil from an external bladder to enter into the pressure hull to an internal bladder, decreasing vehicle volume, causing the vehicle to descend. (AUVAC, 2012)

The most significant shortfall with the thermal glider is the necessity for a 10 C temperature difference for operation. This limits the use of thermal gliders to approximately 65 percent of the world's oceans (C. Jones, Allsup, & Altshuler, 2010). Additionally, to speed heat transfer, the heat exchange tubes are normally placed external to the vehicle. (See Figure 19 for reference.) Placing the heat exchanger tubes external to the non-pressure hull or fairing adds an additional encumbrance with regard to debris accumulation and has a detrimental effect on vehicle drag. The above however, neglects the significant energy savings from the use of the readily available thermal cycle. There is no energy cost (pump operation) for the cyclic motion of the glider thus the available battery energy is utilized to operate the pitch/roll controls and sensors. This

energy savings results in a substantial increase in flight duration relative to an electric glider for the same battery configuration (number & type).

The main drawback of the thermal glider is its limited efficiency.

The thermal cycle has a very low efficiency, approximately 3%, due to the small temperature differences. The low efficiency itself is not a handicap since there are large sources and sinks of heat, however, the low efficiency means a large heat flow relative to the useful work that is done. Therefore, the glide path of a thermal glider is almost double that of the electric gliders. This is necessary to constantly harvest the oceans energy for glider usage. (Webb, Simonetti, & Jones, 2001b)

3. Wings and Stabilizer Surfaces

The wings, or airfoil shapes, utilized on conventional underwater gliders (Spray, ANT, Slocum Electric and Thermal, SeaGlider) are symmetrical for gliding upward and downward and are thin flat wings with sharp leading edges (Webb, Simonetti, & Jones, 2001a). The wings are positioned at an angle of approximately 45 degrees to the main longitudinal axis (fore/aft) of the glider.

The wing span and foil shape vary dependent on the overall dry weight of the glider, buoyancy of the glider and the desired 'forward' speed characteristics. The relatively sharp angle of the wings prevents debris accumulation on the lifting surfaces. The wings on some production models (SLOCUM Electric or LBS) are also removable for shipping and stowage and are installed only during pre-launch preparations. The glider Spray also uses the wings to house the antenna for the iridium satellite up/down link function.

Two exceptions to the use of relatively large wings to generate lift are the eFolaga (no wings, smooth body) and the SeaGlider (no wings, but aft lifting surfaces in place of wings). eFolaga uses a jet pump aft to generate thrust and induce forward motion of the vehicle in place of the buoyancy force coupled with the lift generated by the flow over fixed wings. The lack of wings reduces the possibility of any debris accumulation on the eFolaga vehicle. (Also of note for eFolaga is that the vehicle mission duration is limited to 6 hours at maximum

speed. This pales in comparison to the durations of Spray, ANT, Slocum and SeaGlider. This indicates that although providing more vehicle maneuverability in the short-term, long-term mission duration is significantly impaired.)

The gliders also have either a single fixed vertical stabilizer (Spray, SeaGlider), controllable vertical rudder (Slocum Electric and Thermal) or vertical and horizontal stabilizer at the afterbody (ANT, SeaExplorer). These serve to both stabilize flight and to control the turning of the glider to follow the ascribed flight path as described in the section which follows.

4. Control (pitch, yaw, roll)

For all subject vehicles, pitch is primarily controlled by movement of liquid (oil/water) from internal to external reservoirs relative to the pressure hull. Fine-tuning of pitch is accomplished by minimized longitudinal motion of battery pack(s) within the vehicle pressure hull. Longitudinal motion of the battery pack(s) effectively changes/reverses the separation distance between center of gravity and center of buoyancy. This allows battery packs to serve dual functions: energy for sensors, pumps, valves and ballast (as required).

For the Slocum gliders, a vertical rudder at the aft portion of the vehicle is operated by the onboard vehicle control system to provide the desired turning rate characteristics. This eliminates roll from vehicle motion allowing the altimeter to function correctly without waiting for the vehicle to stabilize. Other vehicles, such as Spray, incorporate a separate, rotational, battery pack to induce roll and thus turning. This is described further below:

This gives the lift vector a horizontal component and induces vehicle sideslip in the plane of the wing in the direction of the buoyant force. The horizontal component of lift provides the centripetal force for turning while sideslip acting on the vertical stabilizer produces the yaw moment needed to change vehicle heading. For example, to turn right during descent the right wing is dropped, like a conventional airplane, generating a lift component to the right that drives the vehicle to the right. Sideslips down and to the right acts on the vertical stabilizer causing the nose to

yaw to the right. To turn right in ascent the glider is rolled oppositely by dropping the left wing. (Davis, Eriksen, & Jones, 2002)

Additionally, the aft position of the wings relative to the glider nose determines its turning mechanism. For instance, Sea Glider's wings are considerably more aft than Spray's resulting in opposite turn characteristics.

The wing is so far aft that the turning dynamics are opposite that of Spray. In descent, to turn right the vehicle's left wing is dropped so that lift on the wing drives the stern to the left, overcoming lift off the vertical stabilizer, and initiating a turn to the right. Hydrodynamic lift on the sideslipping hull produces the centripetal force to curve the course. Conversely, in ascent a roll to the left produces a turn to the left. (Davis, Eriksen, & Jones, 2002)

For eFolaga there is no roll control as the vehicle was designed as roll neutral and thus there is no roll mechanism for turning within the vehicle. Instead pitch and yaw adjustments are accomplished via the use of thru hull jet thrusters to provide yaw and pitch control. This allows relatively horizontal attitude of the vehicle for all maneuvers which may be useful for certain sensor packages (i.e. bottom imaging or side scan sonars).

5. Sensors Wetted and Non-wetted

A number of sensors are either standard equipment or available as options on underwater gliders, see Figures 3 thru 7. The standard equipment usually includes a Conductivity, Temperature, Depth (CTD) sensor, compass and altitude. Any additional sensors are incorporated into a payload bay or within the existing wet space forward or aft of the pressure hull and under the fairings. Dependent on the sensor utilized the energy consumption may increase and result in reduced mission duration times. To overcome this issue glider makers such as Webb Research (Slocum) offer an extended battery variant. For sensors, the trade-off is between sensor need/data value, energy consumption and mission duration requirements. Additionally, the glider must be capable of providing the control necessary for the given sensor. For instance, side scan sonar has severe requirements on allowable vehicle roll, therefore a comparison

of the sensor specifications versus vehicle capabilities is mandatory before considering the installation of any sensor on the vehicle. Additionally, the effects of changes in vehicle center of gravity and center of buoyancy on flight characteristics must be understood.

6. Communication/Navigation

Communications/navigation fixes from the underwater glider to the remote underwater glider control station (or stations) are conducted during vehicle surfacing and subsequent exposure of the Iridium satellite or GPS antenna. Exposure of the antenna is initiated by increasing aft buoyancy for trailing and built-in (rudder) antenna variants (Sea Glider, ANT and Slocum, eFolaga, SeaExplorer, respectively). This results in a significant down-angle of the vehicle relative to the vehicle's nose.

Uniquely, Spray utilizes an antenna which is built into its wing and uses the rotary battery ballast to roll the vehicle (and corresponding wing) approximately 30 degrees out of the water.

With the antenna exposed communication with the control station occurs with data being uplinked and new mission profiles being downlinked. The glider then submerges and begins its new mission with the corresponding updated mission profiles.

7. Launch and Recovery

The seven gliders considered for the architecture study are all launchable from surface platforms. Glider launch is accomplished by manual launch over the side by two personnel from a small boat such as a Rigid Inflatable Boat (RIB) (eFolaga, SeaFlider), by lowering the vehicle into the water with a davit crane and specialized launcher (if available), or can be launched from launch rails at the side of the vessel. Spray launch with a davit alone and with a specialized fixture and davit are shown in Figures 26 and 28, respectively. Slocum Electrics launch from launch rails at the side of the vessel is shown in Figure 29.



Figure 27. Spray Glider Launch w/Strap & Davit from (Krupski, 2012)



Figure 28. Spray Glider Launch Fixture from (WHOI, 2012)



Figure 29. Slocum Electric Launch from Surface Ship Guide Rails from (Quest Marine Services, 2007)

Recovery of the gliders are accomplished by using a boat hook to pull the glider back up the launch rails, hoisting the glider back onboard a RIB manually, using the mother ship's davit and a recovery cage (see ANT Figure 14) or utilizing a davit and attaching to the built-in recovery ring on the glider as shown for Spray (aftmost point) in Figure 13.

Launch of a glider from a submarine's Dry Deck Shelter (DDS) was accomplished from the SSN688 class submarine, USS Buffalo, in November 2011 (Rush, 2011). This was aided by U.S. Navy divers, who removed the glider from the DDS and 'launched' it from the aft of the submarine. Note that the DDS has an approximately 2.6 m inside diameter while the glider utilized in the experiment (Slocum, Electric) has a wing span of 1.2m. Launch of a glider from other than the DDS has been considered but would require reconfiguration from a planar to a ring wing configuration as noted in (Alvarez, 2010). However, this paper did not address the disparity between the inside diameter of conventional torpedo tube (approximately 21- inch) and the diameter of the ring wing (10-inches). For instance, there was no discussion on how the modified glider would

be supported within the torpedo tube structure. The recovery of the glider was conducted at the surface utilizing a RIB. Future plans call for the divers to recover the glider and return it to the DDS.

As an alternative to torpedo tube launch, launch from large diameter missile or payload tubes appears feasible. Large diameter missile tubes are present on SSBN and SSGN Class submarines and are scheduled to be installed on SSN774 Class submarines starting with Block IV. Within the large diameter tubes, supporting structure would be required to both secure the glider in the large diameter tubes (~84" diameter) and allow vertical launch of the gliders. Additionally, due to the limited buoyancy of underwater gliders, a launch pulse or supplemental buoyancy may be required to ensure safe separation of the glider from the platform.

D. CHAPTER SUMMARY

This chapter down selected from the underwater gliders surveyed in the previous chapter in order to provide a comparison of the associated significant architectural attributes. Although the underwater glider survey resulted in a compilation of both conventional (buoyancy only), hybrid gliders (buoyancy and propulsion) and winged gliders only conventional and hybrid gliders were considered in the architectural attribute discussion. This was necessary to restrain the scope of the resultant architectural attribute discussion. Additionally, the conventional and hybrid gliders that were selected for the architectural attribute discussion have significantly more at-sea time and either higher rates of current production or near-term viable production than the flying wing glider (Liberdade Zray). The gliders that were selected were:

- Spray
- ANT
- Slocum Electric
- Slocum Thermal
- Sea Glider

- eFolaga
- SeaExplorer

The architectural attributes that were examined were comprised of the following:

- Hull
- Buoyancy Mechanism
- Wing and Stabilizers Surfaces
- Control (pitch, roll, yaw)
- Sensors Wetted and Non-Wetted
- Communications/Navigation
- Launch and Recovery

Each glider's architectural attributes were examined in combination with all the other selected fixed wing gliders. This information will now be utilized in the next chapter in order to recommend an underwater glider architecture for use by the U.S. Navy in actual forward deployed conditions.

IV. RECOMMENDATION OF UNDERWATER GLIDER ARCHITECTURE FOR U.S. NAVY USE

A. INTRODUCTION

This chapter delineates the recommendation(s) for an underwater glider for use by the U.S. Navy. This section not only addresses the selection of the architectural features for a U.S. Navy underwater glider but also provides substantiating statements and rationale that justify said selection. The order of selection of the architectural features is identical to that in chapter III and is presented in the following order:

- Hull
- Buoyancy Mechanism
- Wing and Stabilizers Surfaces
- Control (pitch, roll, yaw)
- Sensors Wetted and Non-Wetted
- Communications/Navigation
- Launch and Recovery

Due to the potential deployment of the subject underwater glider from both surface platforms and submarines two potential architectures are recommended in the section, which follows.

B. GLIDER ARCHITECTURAL RECOMMENDATION

1. Hull

The hull for the glider is recommended to be of the type which matches the hull's compressibility to that of seawater as a function of depth. This will reduce the energy required to be provided by the buoyancy system at the deepest point in the dive cycle. Although additional analysis and testing is required to match the compressibility of the hull to the compressibility of seawater

this is considered worth the extra effort and associated cost from a long term operating cost perspective. A hull construct which matches seawater compressibility reduces the amount of fluid which must be stored within the pressure hull. This hull construct also reduces the amount of fluid which must be pumped from within the pressure hull to outside the pressure hull as is normally accomplished for stiff' hulls to compensate for differences in hull compressibility and seawater compressibility. Reducing the volume of fluid pumped across the pressure/non-pressure hull boundary reduces the overall energy consumption for each surface-to-depth cycle. This enables the residual energy to be utilized to instead extend mission duration. The seawater compressibility matching hull ultimately allows thinner hull structures which provides additional volume within the hull due to the reduced heights of stiffening ribs and associated bulkhead thicknesses.

To prevent issues associated with thru hull penetrations, thru hull penetrations should either be eliminated or substantially minimized. This will increase the reliability of the underwater glider which is significant as mission persistence is an important characteristic of underwater gliders mission profile. The hull should be comprised of various wet and dry sections, with the wet sections provided at the furthest points forward and aft, respectively. This will allow placement of flow thru sensors forward (i.e. flow CTD or forward looking sonar) while the aft wetted sections would be used for the inflatable bladder of the buoyancy system. Additionally, any minimal damage to these immediately forward/aft wetted sections would not result in damage to the vehicle pressure boundary. This would either allow continuing operation of the vehicle (with possible reduced capability if allowable) or initiation of an emergency recovery procedure.

2. Buoyancy Mechanism

The recommended buoyancy system is an electrically powered two pump system with a booster pump feeding a main pump to pump fluid from a reservoir

within the vehicle's dry pressure hull into an external bladder located in the vehicle's aft wetted section. This allows improved buoyancy system performance at greater depths of vehicle operation as the pressure across each pump is less than that across a single pump performing the identical function. (Obviously if the glider were limited to shallow depth operation a single pump would suffice. However, this thesis assumes a requirement for a multi-depth of use glider.)

The use of the thermal buoyancy system utilized by Slocum Thermal was considered but deemed overly restrictive in regard to potentially restricting the glider's potential operating areas. As reported in the description of the thermal buoyancy system in Chapter III, only 65% of the ocean is accessible to thermal gliders (C. Jones, 2009). From a tactical usage standpoint this is untenable in many of the current operational areas. Furthermore, the external tubes necessary to increase overall thermal buoyancy engine efficiency are detrimental in regards to debris accumulation on the glider. (Note that this is in addition to any debris which may be accumulated and/or shed from the wings due to the aftward rake of the wings.)

3. Wing and Stabilizer Surfaces

The U.S. Navy has both surface and sub-surface (submarine) assets in its current ship inventory. Of the seven underwater gliders considered in the architectural discussion any winged, finned or pump jet variants could be launched from either surface platforms or from the DDS of submarines. However, if launch from other than the DDS is considered on submarines (i.e. torpedo tube launch) then only jet pump variants (i.e. eFolaga) would be integratable. Therefore, an alternate architecture for propulsion would be required for tube launch from submarine platforms. Noticeably, the limited mission duration of the eFolaga, stated as 6 hours at maximum speed by GraalTech, would not achieve the persistent presence capability of underwater gliders and will not be considered further. Therefore, another vehicle (UUV) for achieving these relatively short missions should be considered.

The relatively short aft fin configuration of SeaExplorer was also considered but eliminated due to the limited lifting surfaces provided by the relatively short horizontal stabilizer (or fin). Thus increased motion of the internal weights (batteries) would be required for pitch control taking up valuable internal volume that could be otherwise utilized.

For launch from surface platforms and submarine DDS structures (by divers) a wing configuration similar to that utilized by the Slocum gliders is recommended in concert with a controllable vertical stabilizer (discussed in the vehicle control section which follows). This provides increased mission duration when coupled with the recommended two-pump buoyancy system. Thus relatively sharp edged wings similarly positioned, as shown on Slocum, would be utilized for the U.S. Navy underwater glider. Incorporation of communications antennas within the wings is not recommended as damage to the wings caused by debris would interfere with the operational mission and eventual vehicle recovery due to lack of communications. However, removable/replaceable wings are recommended as this aids storage of the vehicles shipboard and allows for rapid replacement of wings damaged during recovery operations.

4. Control (pitch, roll, yaw)

With use of the recommended fixed wings as described in Section 3, Wings and Stabilizer Surfaces, vehicle pitch and roll control would be as described for the Slocum Electric and Thermal gliders. Therefore, a portion of the batteries used for buoyancy mechanism and sensor operation would be axially displaced to alter the center of buoyancy/center of gravity separation distance to provide vehicle pitch control. (Note some batteries are stationary in this configuration and arranged to neutrally balance the center of gravity around the center of buoyancy.) The buoyancy mechanism and wings would provide the gross pitch control while the shift in center of buoyancy/center of gravity separation distance would provide vehicle fine pitch control. This minimizes the distance that the pitch mass has to move in the longitudinal direction which may

be acoustically beneficial. Roll control would be affected thru use of a controllable vertical stabilizer at the upper aft portion of the glider. This provides a significantly reduced turning duration as compared to fixed stabilizer gliders with roll control established via a rotational mass within the glider (Wood, 2009). This is particularly important in operations which require more frequent overlap without wasting energy in turn creation (i.e. mine reconnaissance).

5. Sensors Wetted and Non-wetted

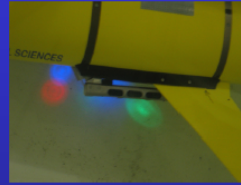
The recommended base sensors for the U.S. Navy underwater glider include the following:

- Sensor: CTD – Conductivity, Temperature, Depth
 - o Use: Data input into the Sonar Equation for higher fidelity Sound Velocity Profiles (SVP)
- Sensor: Altitude
 - o Use: Used by control system to keep glider a fixed distance from ocean floor.
- Sensor: Compass
 - o Use: Input to the glider controller to maintain desired heading.

There are also a myriad of other sensors, which may be integrated into the U.S. Navy underwater glider. An indication of this plethora of sensors is provided in list format in Figure 30 and in hardware format in Figure 31.

Sensor Packages

Acoustic Modem
ADCP
Altimeter
Bathyphotometer (bioluminescence)
Optical Backscatter
Optical Attenuation
Oxygen
Conductivity, Temperature, Depth
Fluorometer
Hydrophone & Arrays
PAR sensor
Radiometer
Scattering Attenuation Meter
Spectrophotometer (red tide detection)



Modular 6 L Payload Bay
Nominally 3 – 6 kg air weight
Customized for a variety of
acoustic, optic and chemical
sensors

Figure 30. Potential Sensor Packages and Modular Payload Bay from (Jones, 2009)



Figure 31. Potential Sensors and Suites from (Jones, 2009)

To allow multiple configurations of sensors without altering the overall vehicle weight and buoyancy characteristics a standardized payload module is

recommended for sensor incorporation. The module should have a specification and an interface control document developed such that minimal or no changes are necessary to the remaining sections of the glider, regardless of the payload integrated or the manufacturer of the payload. This will limit overall life costs of the glider and avoid unnecessary reconfiguration for a specialized payload. However, dependent on the sensor instituted the mission duration or allowable flight maneuvers may be further extended or constrained. For example, sensors which utilize more hotel power (battery power) will result in reduced mission durations from the baseline sensors while sensors such as optics or side scan sonar may limit the allowable flight angle of the glider.

6. Communications/Navigation

The recommended communications system for the U.S. Navy underwater glider includes both Iridium and GPS suites. Note that dependent on the mission area, communications may also require an encryption device (electronics) to prevent data intercept. Additionally, the use of an embedded GPS/Iridium antenna within the previously recommended vertical stabilizer is also recommended. This avoids an additional appendage specifically for the antenna structure and further minimizes thru hull passages.

The use of underwater gliders to map CTD data or gather data with an alternate sensor may be viewed as a hostile act by the threat nation prior to full out invasion. Therefore, it is further recommended that underwater communications capability be included within the U.S. Navy underwater glider (for example the WHOI underwater modem). In this manner, a fleet of gliders could be used as either data gathering nodes or relay stations providing the data back to an underwater hydrophone node or on-station submarine. In threat areas the gliders would be unable to surface to provide data or gather GPS fixes. To avoid visual detection GPS fixes would need to be accomplished during night time hours only. This may result in increased navigational errors as the current recommendation is to use dead reckoning for navigation. If this is untenable

from a data or navigation standpoint then it is further recommended that an Inertial Navigation Unit (INU) be included in the glider's base sensors to provide increased navigation accuracy between actual GPS fixes.

7. Launch and Recovery

The recommended architecture for launch of the U.S. Navy glider is designing multiple features within the vehicle structure to allow; launch directly over the side via RIB and two person team, lowering from surface vessel via davit crane, from guide rails either astern or athwartships or vertically ascending from a submarine's large diameter missile or payload tubes. This will provide maximum overall flexibility in the deployment of U.S. Navy underwater gliders and allow them to be launched from all surface vessels, from the DDS of submarines with diver assistance, and from large diameter missile or payload tube equipped submarines.

No additional features are required for man-launch from the RIB. However, hard points would be required for launch with a davit crane to protect the vehicle hull, sensors and wings. The strengthened boundaries between hulls sections could be used as hard points to lift the vehicle from the surface vessel with the davit and also secure it in the DDS. An arrangement similar to that for ANT shown in Figure 14 is envisioned for launch from a davit crane. For rail launch an arrangement similar to that for Slocum in Figure 25 is recommended for launch from astern/athwartships. Note that launch from deck mounted rails (even with tilt features) requires that the overall vehicle withstand the impulse loads occurring as the glider enters the water and may require additional analysis and structural strengthening. For launch from a submarine's large diameter missile or payload tube a securing and release point on the afterbody similar to that of Spray is recommended, see Figure 13

The recommended architecture for recovery is identical to that for launch with similar features required in identical locations.

C. CHAPTER SUMMARY

This chapter provided the recommended architecture for a U.S. Navy deployed underwater glider. Due to limited mission duration the eFolaga underwater glider was not considered in the architectural recommendations. As the main feature of underwater gliders is persistence on station or gathering data the 6-hour mission duration for the eFolaga could be accomplished by other existing UUVs contained within the UUV Master Plan (U.S. Navy, 2004). Specific architectural recommendations made are shown in Table 1.

Table 1. Recommended Architecture for U.S. Navy Underwater Glider

Architectural Feature	Recommendation
Hull	Seawater compressibility matched composite hull with wetted forward and aft sections and payload specific section.
Buoyancy Mechanism	Two pump system with booster plus main pump, internal fluid reservoir, external bladder in aft section.
Wing and Stabilizer Surfaces	Fixed wing at 45 degree to hull longitudinal axis, thin leading edge. Vertical stabilizer/fin actuated internally both similar to Slocum glider.
Control (pitch, yaw, roll)	Pitch gross control provided by buoyancy system, fine pitch control provided by moveable ballast longitudinally. Yaw control provided by internally actuated vertical stabilizer/fin.
Sensors Wetted and Non-Wetted	Conductivity/Temperature/Depth (CTD), altitude, compass. Separate payload bay with fixed specifications and interfaces.
Launch and Recovery	Structural strengthening and lift point provisions for 2-man launch from RIB, davit crane lift launch from surface vessel deck, launch from tilted rails from surface vessel deck and securing and releasing for vertical ascent from as submarine's large diameter missile or payload tubes. Recovery identical and reverse to launch.

V. OPERATIONAL CONSTRAINTS AND CAPABILITIES OF UNDERWATER GLIDERS

A. INTRODUCTION

This chapter discusses the operational constraints and capabilities of underwater gliders. Specifically, the discussion will focus on what constraints are placed on underwater gliders due to their architectural configurations which subsequently limit the operating envelope of the gliders. For example are they constrained to specific operating areas due to limitations in depth or turning ability. Furthermore, the capabilities of underwater gliders will be delineated in regards to aiding the U.S. Navy's warfighting capabilities. This will provide insight into the military value that underwater gliders bring to the U.S. Navy. Finally, a comparison will be made between capabilities and constraints of underwater gliders as compared to the other UUV sizes notated in the U.S. Navy Unmanned Undersea Vehicle Master Plan (U.S. Navy, 2004).

B. GLIDER CONSTRAINTS

The U.S. Navy glider proposed in Chapter IV has a number of constraints that are inherent in all the gliders investigated in the architectural analysis of Chapter III. The greatest constraint is that of having to surface to transmit data recorded by the underwater glider to remote glider operator locations or nearby U.S. naval units (via satellite or radio frequency link). This places the glider at risk for detection and capture if the operating area is within threat sovereignty territory. This could be avoided by the addition of an underwater acoustic modem such as was noted, in Chapter III, as desirable for the U.S. Navy glider proposed. However, others have noted underwater acoustic modems are detrimental to glider endurance. "When they surface, gliders have a near-real-time data transmission capability via the Iridium or Argos satellite communications systems. Gliders which operate on minimal energy, do not use acoustic modems as they would limit their endurance." (Jane's, 2 JUN, 2011).

Thus, as with all glider sensor integrations, there is a constant tradeoff between sensor utility and need and the endurance of the glider. Therefore, more energy efficient acoustic modems would be needed or increased power density for a given battery cell would be required.

Due to their fixed-wing, buoyant designs, gliders cannot maintain constant position at a given depth (hover) in the presence of ocean current. Instead, when current is present they may be pushed backward by the current (if it exceeds forward speed of the vehicle) while still ascending/descending. Without consideration for current it would be possible to design a control system such that vertical hovering is maintainable. (This is a strong feature of the eFolaga vehicle discarded in the architectural study due to its limited endurance of 6 hours at maximum speed.)

The current dead reckoning navigation scheme (with altitude sensing) limits the ability of the glider to provide truly accurate position data with accompanying oceanographic data. (Note this assumes that the current altitude sensing is done forward of the vehicle to avoid collision with a rapidly rising sea floor.) Additionally, navigational error growth may result in uncertain location with potential future uses such as inclusion of an imbedded side-scan sonar for MCM or object location. Incorporation of side-scan sonar would require significant software and logic development to account for the angle of attack of the glider relative to the sea floor. An option would be the incorporation of an inertial navigation unit (INU) to provide more accurate navigation between GPS fixes at the surface (when allowable).

Another constraint on gliders is that they must have sufficient water depth below-the-surface and altitude above-the-bottom to accomplish their characteristic saw-tooth glide pattern, see Figure 1. The ability of the glider to avoid impact with the sea floor depends on altitude sensing and the responsiveness of the control system to shift ballast and increase buoyancy as

the sea floor approaches the altitude set point (above the bottom). In this context, the relatively slow forward speed of the glider enables the control system adequate time to respond prior to bottom strike.

Existing underwater gliders were not designed with minimizing underwater acoustics signatures as a requirement. Therefore, additional architectural constraints and features may be necessary to avoid detection, tracking and classification of the underwater gliders when conducting a Rapid Environmental Assessment (REA) as part of an overall Mine Counter Measure (MCM) mission. To avoid pump and motor acoustics (vibration, airborne noise) coupling with the hull structure, design approaches such as isolation mounting of pumps and motors from the hull structure may be necessary. Additionally, low noise components such as bearings and gears may be necessitated. Potentially, a noise budget could be allocated for each component of the glider and an overall glider noise level established with the buoyancy mechanism and other systems operational based on a mission profile. Alternately, acoustic noise cancellation techniques could be used to cancel continuous duty cycle acoustics. Such changes will require reassessment of overall vehicle weight and buoyancy and also reassessment of the selection of the buoyancy system components. Increases in overall vehicle size and weight may result as a byproduct of incorporating noise reduction and isolation features.

An issue with incorporation of any additional sensors is retaining the pre-existing endurance levels given the energy consumption of proposed sensors relative-to/in-addition to current sensors. Current sensor selections typically have extremely low power consumption and incorporate a 'sleep' mode wherein the sensor is in a quiescent state, when unused, thus saving valuable energy. For sensors that require a continuous or near continuous duty cycles such as forward looking (obstacle avoidance/navigation) or side scan sonars (MCM) and optical systems (bottom or debris imagery) this would be problematic, as vehicle

endurance would suffer significantly. This would eliminate the persistent presence characteristic of gliders such that deployment of an alternate UUV would be more appropriate.

The proposed underwater glider is constrained to be launched only from a submarine's DDS and with the aid of divers. This is due to the use of fixed wings, whose span is significantly larger than the current U.S. Navy torpedo tube diameters, therefore torpedo tube launch is not feasible. However, if semi-rigid inflatable airfoils were utilized, similar to those on the Loitering Electronic Warfare Killer (LEWK) (Erwin, 2001), repackaging an underwater glider for torpedo tube launch may eventually prove feasible.

Although not specifically a constraint, the use of the dual pump buoyancy system provides an all-depth buoyancy system but at the expense of added weight and complexity at shallower operating depths. Obviously different buoyancy pumping configurations could be feasible for gliders relegated to operate within a specific depth range. However, having multiple configurations of buoyancy pumping systems increases the glider logistics tail significantly.

C. GLIDER CAPABILITIES

The greatest capability of underwater gliders is their ability to maintain a persistent and continuous presence in a specified operating area while gathering and recording critical sensor data. Gliders are being used worldwide to capture conductivity, temperature and depth readings in various operating areas ranging from deep-ocean to shallow-littorals. In 2009, a Slocum Electric glider, from Rutgers University, crossed the Atlantic Ocean in 221 days (Mother Nature Network & Butler, 2009). Following the recent British Petroleum oil rig disaster (Deep Water Horizon Oil Spill, 20 April 2011, Gulf of Mexico) underwater gliders were used to locate and track oil by utilizing the onboard fluorometers which can indicate the presence of oil (NOAA, 2010).

A fleet of gliders could also provide a low cost network for determining the patrol patterns of threat submarine fleets. This is due to the inherent endurance

of gliders previously noted as 6 to 12 months in Chapter II's underwater glider survey. This would require that acoustic events be sensed and recorded by the glider. Acoustic measurements would require the addition of conformal or forwarded mounted hydrophones (ANT-LLC, 2010) to avoid self-noise issues (those related to the glider itself). Alternately, a towed hydrophone array could be deployed prior to or immediately following glider launch. Potentially automatic target recognition (ATR) software could be developed such that the glider would recognize a high value contact and relay the information shortly after the contact cleared the area. Subsequently overlapping gliders would aid in development of an overall submarine patrol track. This is somewhat similar to the plans for the ONR flying wing Liberadade z-Ray (ONR, 2012). Similarly, a network of gliders could provide coastal reconnaissance of any underwater approaches to the U.S. shores and key infrastructures.

The myriad of potential sensor packages for gliders is of considerable significance. This is especially true with the large number of humanitarian efforts being undertaken by the U.S. military in recent years. In particular, continuous detection and monitoring of radiation levels would prove invaluable in monitoring local radiation levels if a disaster occurred at a nuclear plant which was located on a coast. This application bridges the capability of the glider from military to humanitarian applications and may provide useful in recognizing circulation patterns of contaminated water from the Fukushima, Japan earthquake, tsunami and subsequent nuclear disaster.

Gliders are classified as man-portable UUVs in accordance with the U.S. Navy UUV Master Plan (U.S. Navy, 2004). This means they could be launched quickly from small platforms such as a RIB or covertly from the DDS of a submarine (Rush, 2011). These actions would allow underwater gliders to provide REA data that can immediately utilized in MCM missions.

Within the U.S. Navy UUV Master Plan (U.S. Navy, 2004) the employment of gliders is noted as part of the Communication/Navigation Network Node (CN3). The CN3 is the "Enabling undersea node of the Net-Centric Warfare

Sensor Grid” (U.S. Navy, 2004) which will “Provide network connectivity across multiple platforms and the ability to provide navigation aids on demand” (U.S. Navy, 2004). Therefore, per the U.S. Navy UUV Master Plan, gliders are tasked with gathering oceanographic data and providing undersea network conductivity. Although valuable tasking given the high endurance of undersea gliders there are numerous other tasks which could leverage this high endurance capability. Thus, the U.S. Navy Master Plan fails to capitalize on the potential uses of undersea gliders for coastal reconnaissance or submarine patrol trackers.

D. COMPARISON OF UNDERSEA GLIDERS AND OTHER AUVS IN TERMS OF OPERATIONAL CAPABILITIES AND CONSTRAINTS.

The basic comparison between an undersea glider and a AUV is between a simple platform meant for oceanographic CTD measurements (glider) to that of a complex vehicle made for a particular mission (AUV). Either gliders or AUVs can be developed which are functional at either deep-ocean or shallow-littoral depths. The significant departure in capabilities between gliders and AUVs is in terms of overall mission endurance which drives many design aspects. Underwater gliders have endurances in terms of months to years while AUV endurance is in terms of hours or days. Vehicle endurance is a function of the speed at which the mission is accomplished. Higher speed vehicles typically consume energy at significantly higher rates. Thus, the actual mission speed of completion requirement drives the determination if an underwater glider or alternate AUV would be suitable for a given mission.

Currently the U.S. Navy is also pursuing the opposite end of the spectrum from underwater gliders, large AUVs (UUV). This is an attempt to increase the station time of the medium size UUVs bridging the capabilities between underwater glider endurance and AUV capacity. For glider operations, operators are most likely stationed remotely such as at the Stennis glider operations center, Stennis Space Center, MS (Lammons, 2012). In contrast, UUVs normally have a highly trained cadre that functions as a support and operations team for the forward deployed vehicle. As stated in the capability section there is potential for

either coastal trip-wire implementation of gliders or use as detection and tracking vehicles for locating threat patrol submarines. The low cost of gliders relative to other AUVs allows a fleet of gliders to cover a given area versus less coverage with fewer AUVs.

E. SUMMARY

This chapter discussed the operational constraints and capabilities of underwater gliders. The dominant operational constraint of underwater gliders is the need to transfer recorded data and receive instructions from the glider control center. This requires the glider to surface and expose its antenna(s). To prevent detection/capture in perceived threat waters, integration of an underwater acoustic modem was discussed and found to reduce the underwater gliders endurance. Therefore, more efficient underwater modems and higher power density batteries are necessary.

The glider's persistent surveillance and REA capability were discussed and found highly relevant to near-term MCM missions. The persistence surveillance capability was discussed relative to conducting constant surveillance of U.S. coastal areas and in detecting and tracking threat patrol submarines.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. SUMMARY AND CONCLUSIONS

A. SUMMARY

This thesis conducts an examination of the utility of underwater gliders within the context of providing additional U.S. Naval capabilities. The specific research questions posed and their subsequent answers are delineated below:

- ***What are the prevalent architectural features of currently existing commercial undersea gliders?***

Based on a survey of available underwater gliders a compilation of prevalent architectural features is developed. The specific key architectural features or attributes selected for further analysis are:

- Hull
 - Buoyancy Mechanism
 - Wing and Stabilizers Surfaces
 - Control (pitch, roll, yaw)
 - Sensors Wetted and Non-Wetted
 - Communications/Navigation
 - Launch and Recovery
- ***How is undersea glider design driven by prevalent architectural features of currently existing commercial undersea gliders?***

Based on the architectural analysis of the aforementioned key features, a comparison of positive and negative factors affecting the overall underwater glider architecture is performed and is fully described in Chapter III. Prevalent architectural features driving underwater glider design include; type and material of pressure hull (i.e. compressibility compensating or not, aluminum or composite), buoyancy mechanism (full depth or limited depth capability), location

of wings on vehicle body (forward or aft of mid-body), method of achieving pitch, yaw, and roll control (actuated surface(s) or wing location/buoyancy), placement of general oceanographic/payload sensors (wet/dry or within separate payload sensor bay), placement of communication antenna (in wings, stabilizer or trailing appendage) and structural modifications necessary to support underwater glider launch and recovery (lift or hard points).

- ***What are the paramount architectural features for a U.S. Navy undersea glider?***

Specific, supporting, rationale for each recommended architectural feature is discussed in Chapter IV and the proposed U.S. Navy underwater glider architecture is delineated below as taken from Table 1.

- Recommended Hull: Seawater compressibility matched composite hull with wetted forward and aft sections and payload specific section.
- Recommended Buoyancy Mechanism: Two pump system with booster plus main pump, internal fluid reservoir, external bladder in aft section.
- Recommended Wing and Stabilizer Surfaces: Fixed wing at 45 degree angle to hull longitudinal axis, thin leading edge. Vertical stabilizer/fin actuated internally - both similar to Slocum glider.
- Recommended Control (pitch, yaw, roll): Pitch gross control provided by buoyancy system, fine pitch control provided by moveable ballast longitudinally. Yaw control provided by internally actuated vertical stabilizer/fin.
- Recommended Sensors Wetted and Non-Wetted: Conductivity/Temperature/Depth (CTD), altitude, compass. Separate payload bay with fixed specifications and interfaces.

- Recommended Launch and Recovery: Structural strengthening and lift point provisions for 2-man launch from RIB, davit crane lift launch from surface vessel deck, launch from tilted rails from surface vessel decks and securing and releasing for vertical ascent from a submarine's large diameter missile or payload tubes. Recovery identical and reverse to launch.

- ***What are the operational constraints of undersea gliders?***

The dominant operational constraint of underwater gliders is the necessity to transfer recorded data and receive instructions from the glider control center (or remote operator). This requires the glider to surface and expose its antenna(s). To prevent detection/capture in perceived threat waters, integration of an underwater acoustic modem is discussed and found to reduce the underwater glider's endurance. Therefore, more efficient underwater modems and higher power density batteries are necessary for incorporation of underwater acoustic modems in gliders without reduction from baseline endurance levels.

- ***What are the operational capabilities of undersea gliders?***

The greatest operational capability of underwater gliders is their ability to maintain a persistent and continuous presence in a specified operating area while gathering and recording critical sensor data. The glider's persistent surveillance and REA capability are discussed and are highly relevant to near-term MCM mission execution. Additional, potential, capabilities of a fleet of underwater gliders are; use as U.S. coastal trip-wire warning system and also as a low cost network for determining the patrol patterns of threat submarine fleets.

- ***How do undersea gliders compare to other types of AUVs in terms of operational capabilities and operational constraints?***

As compared to other AUV types, the underwater glider is capable of operating nearly autonomously and for longer periods. This is due to the operation of the glider from a remote command center and the significantly longer duration capability of gliders. Overall manning is reduced as operation is conducted from a remote underwater glider command center obviating the need for a large cadre of vehicle specific operational and maintenance support personnel. Additionally, a fleet of underwater gliders could provide undersea network conductivity to various fleet assets at a substantially reduced cost as compared to other AUVs.

B. AREAS TO CONDUCT FURTHER RESEARCH

This study should be re-evaluated once additional open-source information becomes available on the Petrel underwater glider. Petrel is of particular interest as it combines both forward motion due to wing lift and propulsive means by propeller.

An additional area of interest would be the power consumption of various sensor payloads relative to the reduction in glider endurance from the baseline CTD configuration. This would include allow mapping specific glider/sensor combinations to specific missions

Furthermore, to provide a submarine launched glider via the torpedo tube environment, eFolaga and SeaExplorer should be re-evaluated once higher energy density batteries become commercially available. Alternately, efforts could be focused on development of a deployable wing concept that unfolds post-launch.

A focused study on underwater acoustic communications via a distributed underwater network system should be conducted to determine if a communications network can be implanted insitu for future glider or other AUV

usage. Potential data transmit/receive rates and power consumption considerations should be included in the study for both the glider and network.

Finally, a study on the potential for inclusion of an INU in the baseline glider package should be considered to reduce the duration that the glider remains detectable at the water's surface. To be effective, this should be coupled with the underwater communications study cited above.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

- Alvarez, A. (2010). Redesigning the SLOCUM glider for torpedo tube launching. *IEEE Journal of Ocean Engineering*, 35(24), 984.
- Alvarez, A., et al. (2009). Folaga: A low-cost autonomous underwater vehicle combining glider and AUV capabilities. *Ocean Engineering*, 36, 24.
- ANT-LLC. (2010). *ANT littoral glider - developing a new generation of gliders*. Retrieved 5/28, 2012, from <http://www.ant-llc.net/ant%20littoral%20glider.htm>
- ASCA - ALCEN. (2012). *SeaExplorer - autonomous underwater vehicle glider*. Retrieved 6/27, 2012, from <http://www.underwater-gps.com/images/dynproduits/g48.pdf>
- AUVAC. (2012). *Slocum thermal glider configuration*. Retrieved 7/17, 2012, from <http://auvac.org/configurations/view/51>
- BlueFin Robotics. (2012). *Spray glider*. Retrieved 5/28, 2012, from <http://www.bluefinrobotics.com/products/spray-glider/>
- BlueFin Robotics. (2012). *Spray glider specification sheet*. Retrieved 7/11, 2012, from <http://www.bluefinrobotics.com/assets/Downloads/Bluefin-Spray-Glider-Product-Sheet.pdf>
- Caffaz, A., et, al. (2010, March 2010). The hybrid Glider/AUV folaga. *IEEE Robotics & Automation Magazine*, , 31.
- Carlowics, M., & Lippsett, L. (2008). Thermal glider use green energy to fly through the deep blue. *Oceanus*, 46(3), 12.
- Davis, R., Eriksen, C., & Jones, C. (2002). Autonomous buoyancy-driven underwater gliders. In G. Griffiths (Ed.), *The technology and applications of autonomous underwater vehicles* (2002nd ed., pp. 37). London: Taylor and Francis.
- Elvander, J., & Halgleish, F. (2011). *The bluefin spray glider - recent activity*. Retrieved 7/5, 2012, from <http://ego2011.eu/doc/PDF-EGO/Wednesday%2016th/EGO%202011%20-%20Joshua%20Elvander.pdf>
- Erwin, S. (2001, June 2001). Electronic warfare drone developed with commercial technology. *National Defense Magazine*,

- French, D. (2010). *Analysis of unmanned undersea vehicle (UUV) architectures and an assessment of UUV integration into undersea applications*. (Masters in Science in Systems Engineering, Naval Post Graduate School, Monterey, CA).
- Graal Tech. (2011). *Folaga AUV*. Retrieved 7/29, 2012, from <http://www.graaltech.it/documents/folaga.pdf>
- iRobot. (2012). *IRobot 1KA SeaGlider*. Retrieved 5/28, 2012, from <http://www.irobot.com/en/us/robots/Maritime/Seaglider.aspx>
- Jane's Navy International. (2011). *Reading the signs across ocean and atmosphere*. Retrieved 8/15, 2012, from <https://janes.ihs.com.libproxy.nps.edu/CustomPages/Janes/DisplayPage.aspx?DocType=News&ItemId=+++1208675&Pubabbrev=JNI>
- Jones, C. (2009). *Environmental workshop WHOI*. Retrieved 7/5, 2012, from http://media.umassp.edu/mattcenter/environmental-sensors/Teledyne_Jones.pdf
- Jones, C., Allsup, B. & Altshuler, T. (2010). *Slocum glider expanding the capabilities*. Retrieved 7/22, 2012, from <http://geos2.nurc.nato.int/mrea10conf/reports/pdf/Jones,%20Slocum%20Glider%20Expanding%20the%20Capabilities.pdf>
- Kongsberg Maritime. (2012). *Autonomous underwater vehicle - REMUS 6000*. Retrieved 05/11, 2012, from <http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/481519DA1B0207CDC12574B0002A8451?OpenDocument>
- Krupski, A. (2012). *FLoSEE 2011 expedition blog*. Retrieved 7/22, 2012, from <http://flosee2.wordpress.com/2011/09/26/sep-21-day-10/>
- Lammons, G. (2012). *NMOC forecasting for bold alligator*. Retrieved 8/17, 2012, from http://www.navy.mil/submit/display.asp?story_id=65340
- Liquid Robotics. *WaveGlider specification sheet*. Retrieved 6/26, 2012, from <http://liquidr.com/files/2012/06/Wave-Glider-0612.pdf>
- Mother Nature Network, & Butler, K. (2009). *First unmanned underwater glider crosses the atlantic*. Retrieved 8/16, 2012, from <http://www.mnn.com/green-tech/research-innovations/stories/first-ever-unmanned-underwater-glider-crosses-the-atlantic>

- NOAA. (2010). *NOAA, IOOS partners employing underwater gliders and surface radar to assist in gulf water sampling*. Retrieved 8/16, 2012, from http://www.noaanews.noaa.gov/stories2010/20100630_ioos.html
- ONR. (2012). *Liberdade XRay advanced underwater glider*. Retrieved 6/27, 2012, from www.onr.navy.mil
- PMEL Engineering Development. (2012). *Slocum electric gliders*. Retrieved 7/5, 2012, from http://www.pmel.noaa.gov/edd/slocum_glidern.html
- Quest Marine Services. (2007). *Image gallery - science and engineering*. Retrieved 7/22, 2012, from <http://www.questmarineservices.com/gallery/scienceEngineering.html>
- Rush, D. (2011). *Submarine makes first launch of an underwater glider*. Retrieved 7/22, 2012, from <http://www.spacewar.com/news/naval-05e.html>
- Seabird Inc. (16 Apr, 2012). *CTD profiling instruments*. Retrieved 05/11, 2012, from <http://www.seabird.com/products/profilers.htm>
- Simonetti, P. (1992). *SLOCUM GLIDER: Design and 1991 field trials*. ().Webb Research Corporation.
- Stommel, H. (1989). The slocum mission. *Oceanography*, 2(1), 22.
- U.S. Navy. (2004). *The navy unmanned undersea vehicle master plan* ().United States Navy.
- University of Washington. (2012). *SeaGlider specifications*. Retrieved 7/5, 2012, from http://www.apl.washington.edu/project/projects/seaglider/pdfs/seaglider_specifications.pdf
- Webb Research, I. (2011). *Teledyne webb research reaches second milestone of U.S. navy LBS-glider program*. Retrieved 7/16, 2012, from http://www.webbresearch.com/newscenter/Reaches_Second_Milestone.aspx
- Webb Research, I. (2012). *Electric glider*. Retrieved 5/28, 2012, from <http://www.webbresearch.com/electricglider.aspx#>
- Webb Research, I. (2012). *Thermal glider*. Retrieved 5/28, 2012, from <http://www.webbresearch.com/thermal.aspx#>
- Webb, D., C., Simonetti, P., J., & Jones, C., P. (2001). SLOCUM: An underwater glider propelled by environmental energy. *IEEE Journal of Ocean Engineering*, 26(4), 447.

- WHOI. (2012). *Spray glider*. Retrieved 7/22, 2012, from <http://www.whoi.edu/instruments/viewInstrument.do?id=1498>
- Wood, S. (2009). Autonomous underwater gliders . In A. Inzartsev (Ed.), *Underwater gliders* (pp. 499). Croatia: In-Tech.
- Wu, J., & Wang, X. (2011). Dynamic modelling and motion simulation for a winged hybrid-drive underwater glider. *China Ocean Engineering*, 25(1), 97-112.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California