Project Shearwater
Preliminary Design Considerations

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Summer 2012

Executive Summary

This report seeks to provide a preliminary look at the development of an autonomous underwater vehicle (AUV) capable of oversea flight in ground effect. This vehicle would provide scientists with a platform capable of rapid deployment to distant sampling locations without the high operating cost associated with deployment from a research vessel. This provides a unique data sampling platform especially well suited for gathering data from sampling locations which evolve spatially at a rate greater than traditional AUVs can keep up with. Despite military interest in similar technologies for over 50 years, there is no publicly available information on development of such a vehicle. As a consequence this requires expensive preliminary work before developing a comprehensive trade space study for mission optimized development. Early analysis suggested that most required individual component technologies exist. One main area that is insufficiently developed for the purpose of this project is the dual operation plane form between aerodynamic and hydrodynamic flight modes. The majority of this report focuses on understanding the fluid dynamic considerations associated with these dual operation modes.

Contents

Section 1

Project Overview

1.1 Introduction

The purpose of project shearwater is to develop a new class of research craft capable of rapid autonomous deployment. This addresses the current lack of a scientific platform capable of sampling from a set of points that are rapidly changing spatially as well as time critical sampling situations. Earlier work concluded that for the target deployment speed of 45m/s (100mph) the most efficient vehicle type is a wing in ground (WIG) craft. This is based on the Von Karmen chart shown in figure B.1. WIG craft benefit from an increased lift to drag ratio when flying in the ground effect. Although WIG craft are not widely seen, many successful examples exist. Most prominent is the work of R.Y. Alexeyev in the USSR between 1960s -1980s [39]. Various other ground effect specific craft have also been developed which take different approaches to attack the general problems of pitch stability, height envelope limitations, and the high drag associated with preflight takeoff. Features of these designs were taken to match as closely with analogous features of current AUV designs. Although a simplified demo mission was assigned, the design should be scalable to longer and more rigorous requirements. The approach was taken to to develop a WIG with low hydrodynamic drag.

1.2 Mission Senario

The proposed mission scenario will represents a scaled down mission of the end target with all mission components present in a reduced time duration or magnitude. This demo mission will utilize the placement and accessibility of the M1 mooring. This allows for an areal flight distance of about 20 miles to the center of the Monteray Bay as shown in figure 1.1. The vehicle will be launched just outside the Moss Landing Harbor entrance from the water. The vehicle will takeoff and fly to the M1 mooring where it will dive to 200m and preform submerged operations for 8hrs at 1.5m/s. Upon completion of the science mission it will surface, take off and fly back to the harbor entrance for recovery. The general mission diagram can be seen in figure 1.2 and summarized in table 1.1.

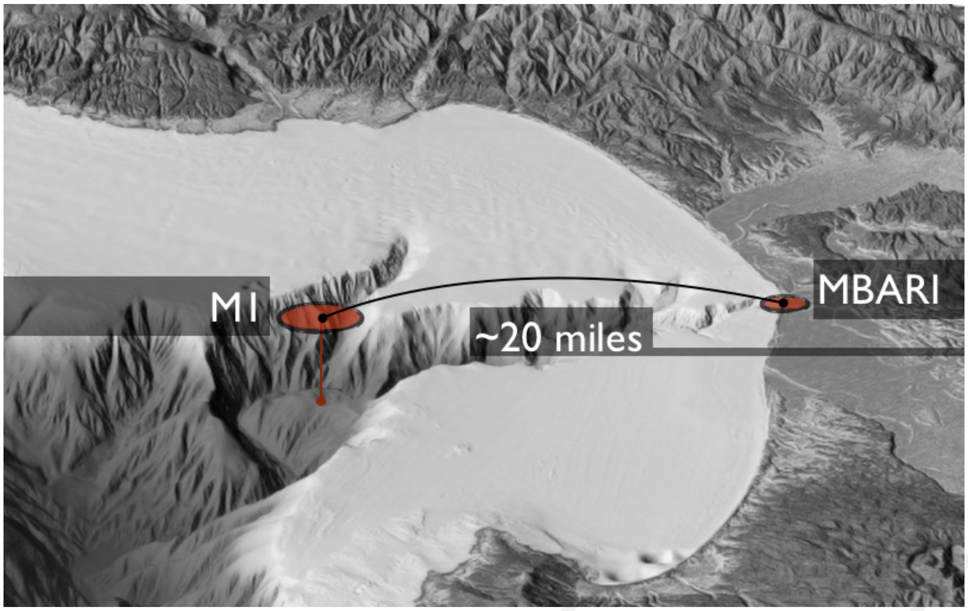

Figure 1.1: Launch Diagram

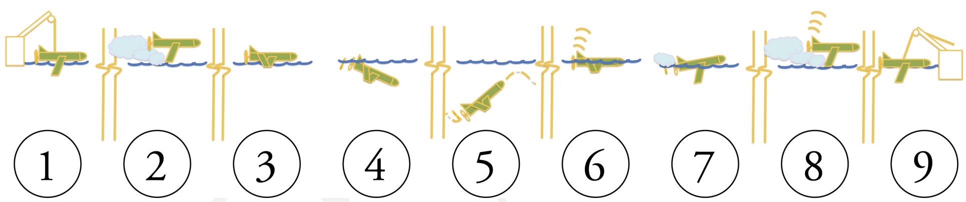

Figure 1.2: Launch Diagram

Table 1.1: Mission Event summary

Mission Segment	Summary
1	AUV unloaded and takes off from water
2	Flight cycle
3	Prepares for water and Lands
4	Submerges
5	Preforms underwater mission
6	surfaces for data transmission
7	Prepares for air and takes off
8	Return flight
9	lands for capture

1.3 Scientific Goals

1.3.1 Sample Recovery

Recover 5 100mL samples to return for additional testing.

1.3.2 Conductivity-Temperature-Depth (CTD)

Unit specs based on Tethys

1.3.3 Submerged Depth

200m

1.4 Payload

1.4.1 Science Equipment

1.5 NAV Package

1.5.1 Accuracy and Response Time Requirements

Further detailed analysis required for this section.

Inertial Measurement Unit IMU

GPS

1.6 Obstacle avoidance

1.6.1 Obsticles

Waves / Surface Roughness

For the purpose of the proof of concept craft a Beaufort scale number of 3 was specified. This translates into a maximum swell of 0.5 meters. [50]

Animals

Various marine animals are likely to present possible problems. Propellers should be protected for safety of both the marine life and vehicle. Flocks of densely packed low flying birds could also cause sensor errors if mistaken for sea surface.

Other Craft

One of the largest obstacle concerns from a severity of consequence perspective would be encounters with maned craft. The speed difference between this craft and lower speed ships requires that this craft be able to avoid other craft without a mutual response. Ideal avoidance would be through a horizontal turning maneuver rather than a vertical jump due to limitations in stable height envelope.

Land

This should be a relatively easy avoidance problem due the static and well mapped nature of land masses. Accurate areal depth measurements could greatly aid mission efficiency in shallow and near shore regions. Arctic missions place another requirement on iceberg avoidance and tracking.

1.6.2 Possible Instruments

A comprehensive analysis of instrument package is required in further analysis. Superficial analysis of the instrument was preformed based on power requirements of AUV and UAV sensor packages. The power requirements for the instruments in both operational modes were estimated to be significantly less than propulsion requirements.

Conditional Accuracy - Fog

Due to high frequency of fog in many marine locations the selected sensor package needs to be robust in low optical visibility conditions.

Sonar

Dual purposed Ultrasound rang finding and Sonar transducers should be investigated for operation in and out of water.

Radar

Lidar

Optical

1.7 Communication

Communication setup needs to be examined in further detail.

1.7.1 Radio

data rate

range

1.7.2 Iridium Satelite Connection (Lband)

data rate

range

1.7.3 Microwave

data rate

range

1.8 conclusions

It is important to reiterate that these are not trivial details and need to be properly addressed but for the purposes of a first order concept design they have little governance on the fluid dynamic or structural design of the craft. This is due to the substantially larger power requirements for propulsion during flight and take off (30W vs 30kW). The instrument power requirement was roughly based off of Tethys AUV requirements.

The propulsion power requirements was based on curve fits from a payload to total WIG craft curve fit using the weight of Tethys as the payload [39] [75].

Section 2

Concept Design Process

Due to time constraints the various concept designs were assessed in a mostly qualitative manner. A large driver in the design of WIG craft is in controlling the pitch stability. Previous designs of WIG craft used vary large horizontal tails or a set of tandem wings to control this [39][55]. In both cases a large drag penalty is associated. For the proposed craft a significant portion of the operation time of this craft will be spent underwater, where stability benefits from the tail are greatly reduced. This dramatically increases the drag penalty of these large tail designs for underwater operation [33]. Several drag reduction options were explored and discussed in Section **??**. Buoyancy change was also determined to be a technology driver in this design. Four concepts designs were created taking into account the key tech drivers discussed.

2.1 Wing Design

Wing design for a WIG craft presents a complex optimization problem due to the number of coupled effects. Airfoil cross sections can not be isolated to a 2D analysis due to the 3D nature of ground effect. Ground effect wings are typically very low aspect ratio further reducing the validity of a 2D approximations. Another large concern for WIG craft is stability which relies on knowledge of the total craft such as CG and rotational inertia. This vehicle inherits these difficulties along with all the aspects of submerged use. Some of these additional concerns include buoyancy control and drag consideration for water. Unfortunately due to the number of interdependent design aspects an elegant analytical optimization scheme wasn't found. Instead the design strategy followed more of a brute force iterative approach. The following provides several different wing concepts.

2.1.1 Wing Morph

Reducing drag in submerged operation is desirable due to the reduced power availability options available and greater proposed operation time in this mode. One solution to this problem is to morph the wing between uses. This has been an active area of research for many years with many proposed concepts. Most of these concepts are far from being flight ready due to material requirements. This leaves just a couple conventional mechanical based designs. There are many variations of these designs but they can be broken down into two main groups telescoping and swing arm. Since the aspect ratio of the wing will be low a telescoping design seemed like the better option of the two.

2.1.2 Neutral airfoil design

This approach again works under the assumption that it is critical to minimize drag in water. The concept being that the wing form and hull has the lowest drag possible with no consideration given to lift characteristics at a 0deg angle of attack. This comes out to be a neutral profile but even a neutral profile generates lift when given an angle of attack (even if isn't efficient). The key point of this design would be manipulating buoyancy such that in water the neutral angle is 0degs of attack and in air the neutral position results in an optimal angle of attack for flight.

2.2 Buoyancy Control

There is a drastically different standard density when comparing an aircraft with a submarine. Submarines are right around the density of water where as aircraft are typically much less than half the density of water. In order to satisfy both of these conditions a large change in buoyancy is required in switching between these two modes. This can be done actively or passively. Simply allowing water to flow freely under the fairing and in the wings may not be acceptable due to difficulty of take off. Take off is the most power intensive stage of WIG craft flight making it essential that the craft float as high out of the water as possible to reduce drag. possible ways of evacuating water from inside the craft include pumps compressed air and passive draining due to inertia from take off acceleration. Compressed air seemed like the best option in terms of energy density and robustness. Many times the volume of the craft can be stored in a miniature scuba tank.

2.3 Propulsion

The selection and sizing of a propulsion system requires a solid understanding of the lift and drag characteristics of craft. For this reason detailed analysis of the propulsion requirements was not possible for this early level design. Some general guides could be established from past WIG craft. Due to the relatively low maximum target speed the most efficient propulsion type is a propeller. Since a greater amount of thrust is required at lower speeds rather than cruising speed the propeller is more efficient if ducted. Again looking at trends for other WIG craft based on a 330kg mass a power estimate of approximately 30kW can be obtained. This is very crude but at least gives a starting point. Propulsion requirements in submerged mode are easy to calculate but require an accurate drag value and there for require a defined outer geometry before determination.

The power source was briefly looked at. This too needs further analysis. Preliminary assumptions assume that subsurface operations will be battery powered and flight operations will be powered by liquid fuel. This hybrid needs to be further analyzed for a weight comparison between series or parallel operation. Other fuel methods such as fuel cells do exist but currently suffer from weight and price [51].

2.4 Power Requirements

Again operational power requirements for Navigation, Control, and Sensor Payload still need to be accessed. The following provides an outline broken down into the respective modes of operation to better access the power source targets and understand the impact on mission design.

2.4.1 Take off

2.4.2 Landing and Submersion

2.4.3 flight operations

2.4.4 submerged operations

2.4.5 Total Power Model

Section 3

Vehicle Design Concepts

One of the primary factors limiting more detailed design is gaining a quantitative understanding of fluid dynamics, specifically gaining lift and drag values. CFD was implemented to begin transitioning from qualitative to quantitate descriptions of the design options. As described previously it is difficult to isolate any specific design aspect. For this reason designs were analyzed in their entirety based on 3D cad models as shown in figure 3.1

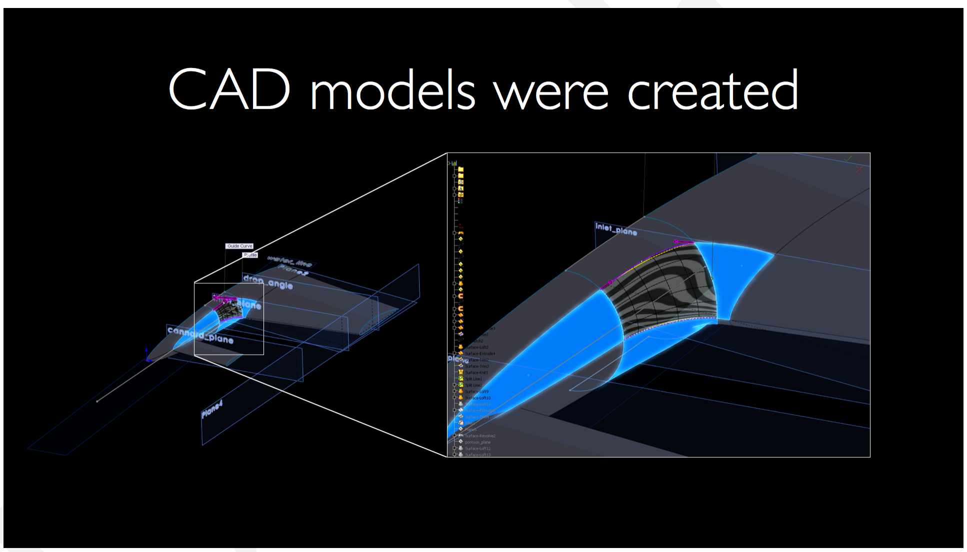

Figure 3.1: Surfacing CAD screen shot

3.1 Blended Body

Optimized for least amount of drag in water. This design utilizes a neutral airfoil. Curved wings act as a twin hull in take off. The triangular rear is the geometric result of a positive angle of attack during take off, downward curved wings and the intersection plane of the water's surface.

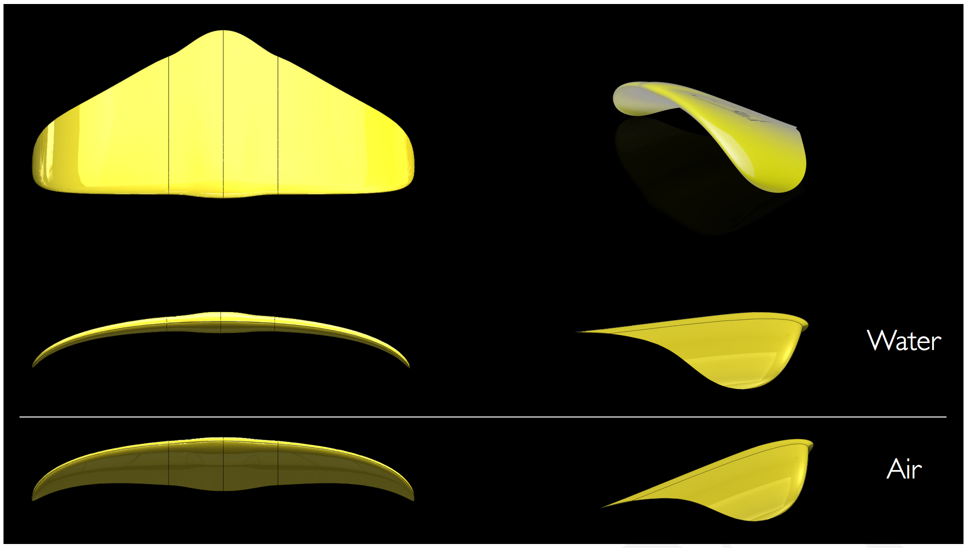

Figure 3.2: Blended Body concept

3.2 Chime Concept

Intended to improve stability and wanter impact over the blended body design by adding a forward lifting surface that can also be reenforced to impact the water from air. The intension is that after impact the wave will propagate outward there by reducing the load on the larger wing area.

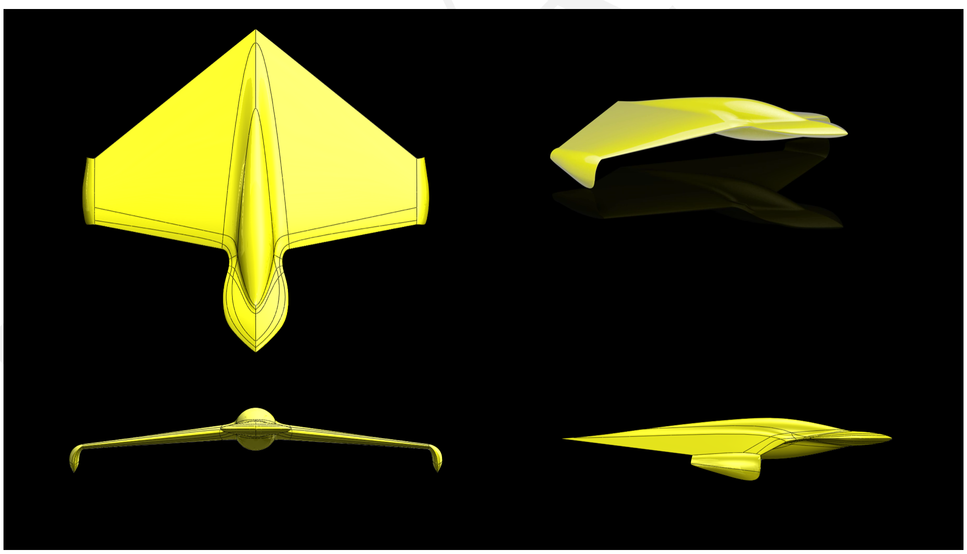

Figure 3.3: Chime concept

3.3 Tandem

The tandem concept utilizes the inherent stability of Jörg craft. Additionally this design incorporates a telescoping wing morph. Wing material could utilize lightweight sail material.

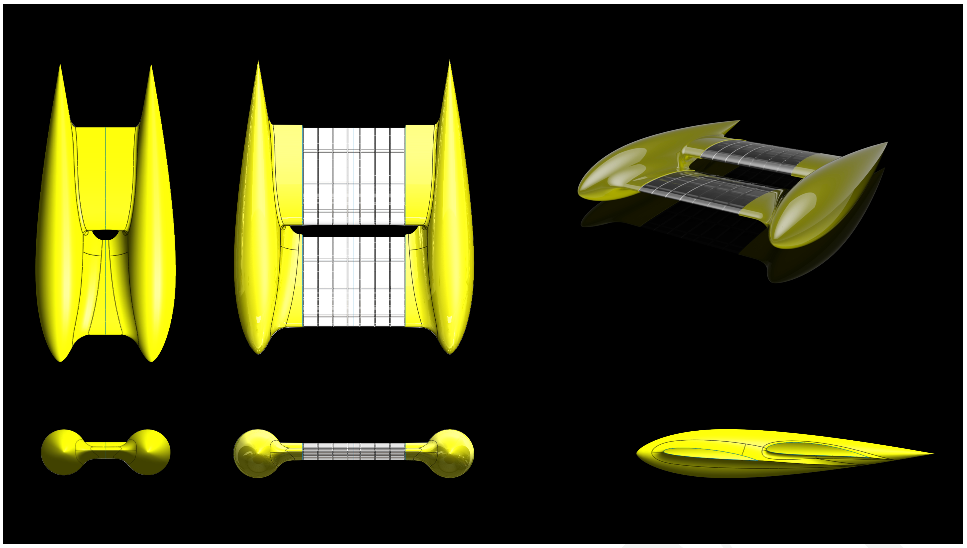

Figure 3.4: Tandem Concept

3.4 Canard

The canard concept attempts to incorporate stability without the drag of a large tail while maintaining better scalability than Jörg craft. This design uses Clark-Y wing profiles due to their flat underside. This is to avoid the Venturi effect associated with curved undersides in ground effect. The canards also allow for greater lift than chimes and naturally lend the craft to pushing propeller setup, ideal for submerged use.

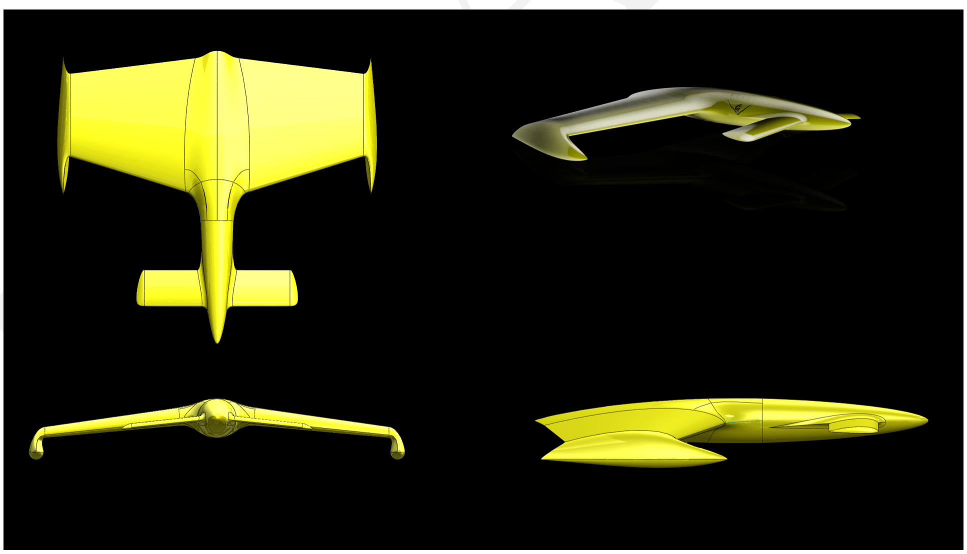

Figure 3.5: Canard Concept

Section 4

Tests and Results

4.1 CFD analysis

Computer simulation was the primary tool for quantitatively accessing proposed designs. This was due largely to the difficulty of accurately instrumenting an appropriate test setup. CFD was implemented using Autodesk Simulation CFD 2012 software package. The investigation only looked at effects of pitch so the model simulations were symmetric allowing for half models to be constructed. Basic setup involved an artificial wind tunnel to be created around the model. Dimensions of this volume were created based on user manual recommendations to avoid edge effects. The boundary conditions were defined based on recommendations of previous WIG CFD analysis with a moving ground velocity [34]. A K-ϵ turbulence model was used.

Although all 4 concept designs were analyzed using CFD, early trials were run with inappropriate parameters. Due to time constrains only results for the Canard case were repeated and reported below.

fluid	height[m]	angle[deg]	Fx(wing tension)[N]	Fy(lift)[N]	Fz(drag)[N]	area[m^2]	L/D
air 45m/s	1	5	364.833	2195.01	-333.644	9.61481	-6.578898467
air 45m/s	0.75	5	657.842	3928.89	-316.851	9.62283	-12.39980306
air 45m/s	1	0	148.544	1042.64	-204.274	9.62562	-5.104124852
air 45m/s	inf	5	364.833	2195.01	-333.644	9.61481	-6.578898467
water 1.5m/s	inf	0	96.6583	760.25	-215.658	9.58977	-3.525257584
water 1.5m/s	inf	5	319.598	1976.13	-320.672	9.61688	-6.162465073

4.2 Scaled Model Test

After preliminary CFD simulations the canard design was selected for further investigation in scaled model tunnel test. Due to time constrains it wasn't possible to design, fabricate and calibrate a sting for use with the model. Instead Flow visualization was used to qualitatively access the model. The design was scaled such that the wing span fit within the 9in envelope. The model was designed to incorporate 8 dye tubes, with 4 colors symmetric across both wings.

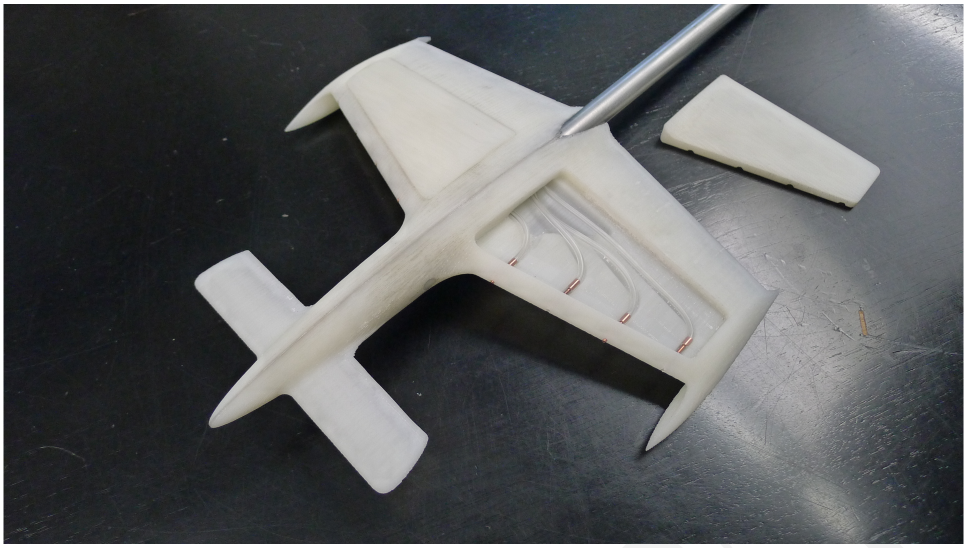

Figure 4.1: Model Dissasembled

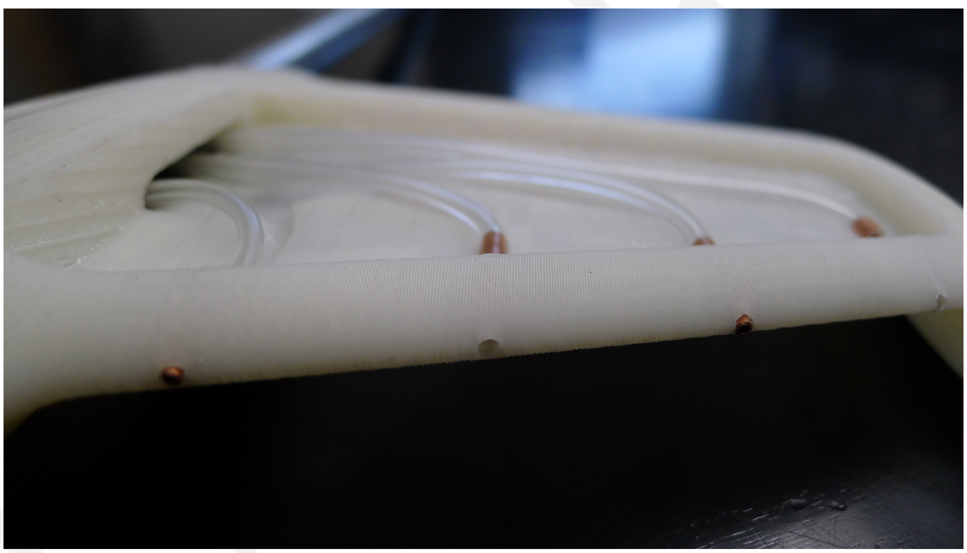

Figure 4.2: Closeup on dye tubes

4.3 Flow visualization Results

Flow visualization was preformed using a closed loop water tunnel curtesy of NPS. The test allowed for a qualitative check on bazar flow patterns. It is somewhat unclear how much the test setup simulated the actual situation since Re number similarity was not achieved and ground effect wasn't simulated.

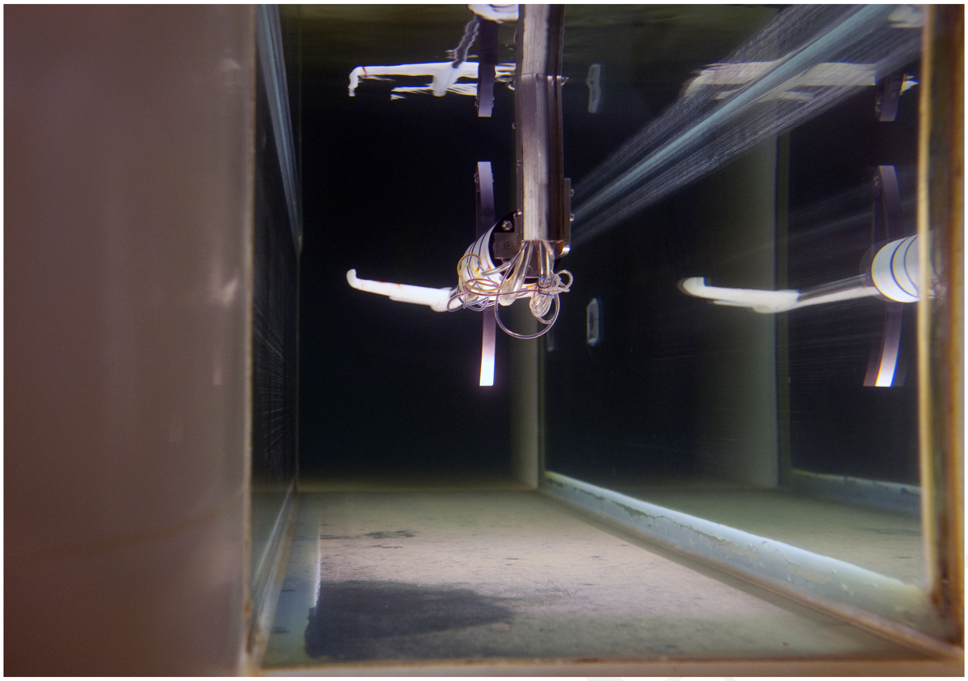

Figure 4.3: Flow tank setup

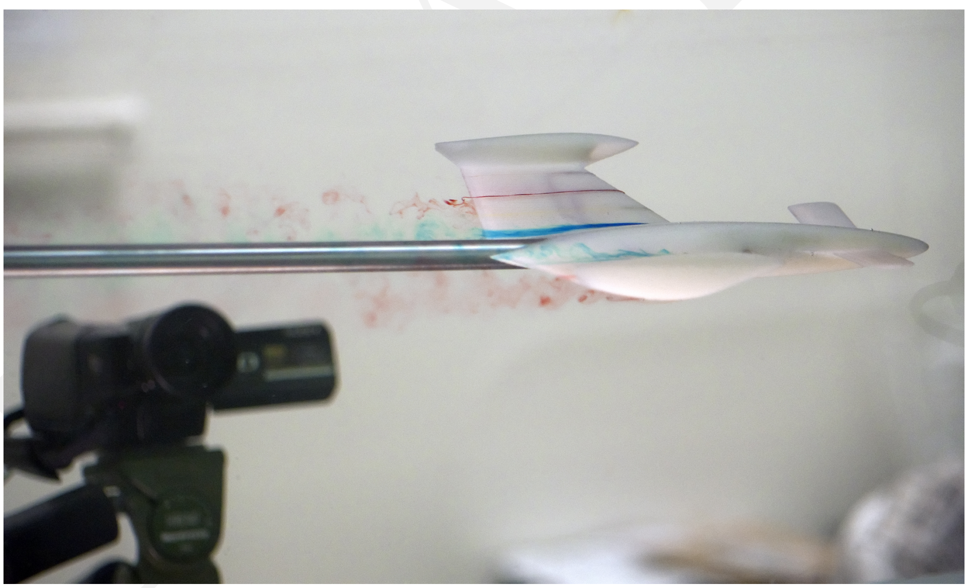

Figure 4.4: Flow tank setup

Section 5

Acknowledgements

I would first like to acknowledge Bill Kirkwood who afforded me the opportunity to share in the development and his vision for Project Shearwater. His mentorship and support over the ten week internship was greatly valued. I feel fortunate of had this opportunity, all of which was tirelessly facilitated by the efforts George Matsomato and Linda Kuntz. I would also like to thank the rest of the MBARI staff as well as the David and Lucile Packard Foundation for making this experience possible through their support and funding. This project was also made possible through the gracious support and access of NPS and their facilities.

Section 6

incomplete references

The following references are awaiting in text citation location.
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Appendix A

Matlab code

A.1 Re Number calculations

```
% >>>                Shearwater Design Calculations                    <<<
% >>>                                                                  <<<
% >>>                     Fluid Scaling Calcs                          <<<
%
%
% Justin Tucker
% July 6, 2012
%
% ====================================================================
% //////////                    NOTES                      \\\\\\\\\\\\
% ====================================================================
%  1.  ALL CALCS IN Kg - Meter - Sec
%
% ====================================================================
% //////////             MAINTENANCE FUNCTIONS             \\\\\\\\\\\\
% ====================================================================
%
% MATLAB clean up from last activity
clear all ; clf; close all; clc;
%
%
% ====================================================================
% //////////              Renolds number scaling           \\\\\\\\\\\\
% ====================================================================
%
% >> This section calculates the Re number of the proposed craft in water
% and air for a preliminary wing span/ craft size

characteristic_length = 2; % [m] wingcord
velocity_air = 45; % [m/s] 100mph=45m/s
velocity_water = 1.5; % [m/s] 3knots=1.5m/s
kinematic_viscosity_air=13.5754 * 10^-6; % [m^2/s] at 10 C interpolated from
% http://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html
kinematic_viscosity_water= 1.307* 10^-6; % [m^2/s] at 10 C from
% http://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html
Re_air = velocity_air * characteristic_length / kinematic_viscosity_air

Re_water = velocity_water * characteristic_length / kinematic_viscosity_water
```

Appendix B

Charts

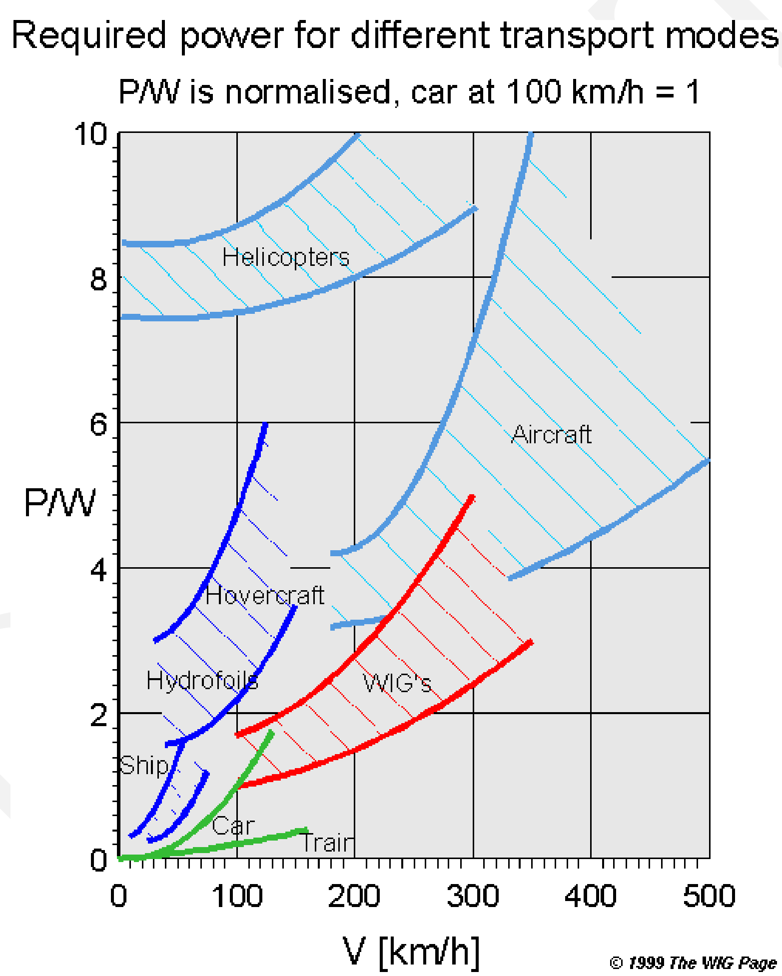

Figure B.1: Von Karman Chart showing WIG efficiency range