PROJECT SHEARWATER

PRELIMINARY DESIGN CONSIDERATIONS

Bailey Hoover, Colorado School of Mines
MBARI Mentor: Bill Kirkwood
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List of Symbols

D	Drag
L	Lift
T	Thrust
W	Weight of AUV
ρ_{sw}	Density of sea water, 1026 kg/m^3
ρ_a	Density of Air, 1.225 kg/m^3
υ_{sw}	Kinematic viscosity of sea water m^2/s
υ_a	Kinematic viscosity of air m^2/s
V	Velocity
C_D	Coefficient of drag
C_L	Coefficient of Lift
K	Lift dependent component of drag
AR	Aspect Ratio
e_w	wing efficiency
S	Shape Factor
q	dynamic pressure
η	efficiency
R	Turn Radius
ω	Angular Velocity
n	Load Factor
g	Gravity (9.81 m/s)
θ	Angle from surface of ocean

Section 2 (EDITS FROM JUSTIN TUCKER SHEARWATER)

The selection and sizing of a propulsion system requires a solid understand of the lift and drag characteristics of craft. For this reason detailed analysis of the propulsion requirements was completed at a later date. (A1) 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 one 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 therefore require a defined outer geometry before determination.

The power source was briefly looked at. This too needs further analysis. Based upon the propulsion designs, subsurface operations will be battery powered and flight operations will be powered by liquid fuel. (A2) This hybrid needs to be further analyzed for a weight comparison between series or parallel operations. Other fuel methods such as fuel cells do exist but currently suffer from weight and price [51].

1 Project Overview

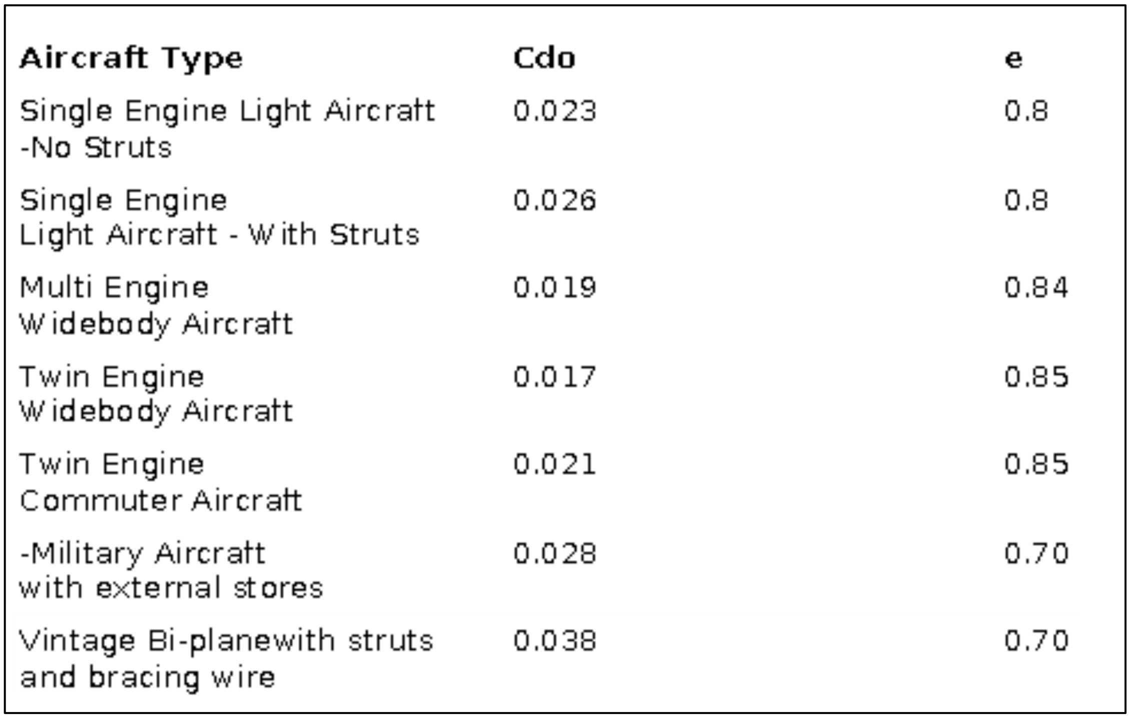
The purpose of this project is to design a propulsion system to sustain by hydrodynamic and aerodynamic flight abilities for a new class of research craft: the Shearwater Autonomous Underwater Vehicle. This project seeks to address existing issues with rapid deployment to distant locations and the high cost of research vessels used for AUV deployment. Previous design for the Shearwater included developing the hull and body shape of the AUV as well as generating preliminary ideas for future design. Based upon the findings and design Shearwater incorporates a canard aircraft concept used in ground effect. This design is favorable with a pushing propeller design and therefore works well with dual submerged use. The purpose of this report is to determine what type of propulsion system is compatible for both aerodynamic and hydrodynamic flight.

2 Propulsion Design Concepts

The selection and sizing of the propulsion system requires an in depth analysis of lift and drag characteristics for both hydrodynamic and aerodynamic flight. Reynolds number calculations verified similar hydrodynamic flow and aerodynamic flow permitting the design of a dual operational research AUV. Propulsion requirements were evaluated separately for flight operations and subsurface operations; initially determining the coefficients of drag and lift. In order to properly make these calculations a few parameters and unknowns were designated. These include the weight of the AUV, range for flight, dimensions, speed and density for both air and water. From these values and equations for drag, lift, thrust, power, climb performances and steady flight performance were evaluated. Through determination of the power requirements for flight and submersion the available motors capable of working for our design were reduced. The focus for the propulsion system is to determine what existing technology can be used to develop a low cost and reliable system. Hybrid design of the propulsion system allows the two system requirements to be evaluated separately and then evaluated for a design that is compatible for both—understanding that the most efficient or ideal design for the individual modes may not be the ideal components for the Shearwater.

2.1 Drag and Lift Coefficients

When considering the drag calculations for aircraft two main components are recognized: drag from the form of the aircraft as well as induced drag from lift. The coefficients of drag were estimated by a Reynolds number/ coefficient of drag chart and a nominal base drag value based upon the class of aircraft. [1] These values are summarized in table 1.1 and figure 1.1, assuming an airfoil form and a single engine light aircraft, without struts.



Aircraft Type	Cdo	e
Single Engine Light Aircraft -No Struts	0.023	0.8
Single Engine Light Aircraft - With Struts	0.026	0.8
Multi Engine Widebody Aircraft	0.019	0.84
Twin Engine Widebody Aircraft	0.017	0.85
Twin Engine Commuter Aircraft	0.021	0.85
-Military Aircraft with external stores	0.028	0.70
Vintage Bi-planewith struts and bracing wire	0.038	0.70

Table 2.1 Nominal Base Drag

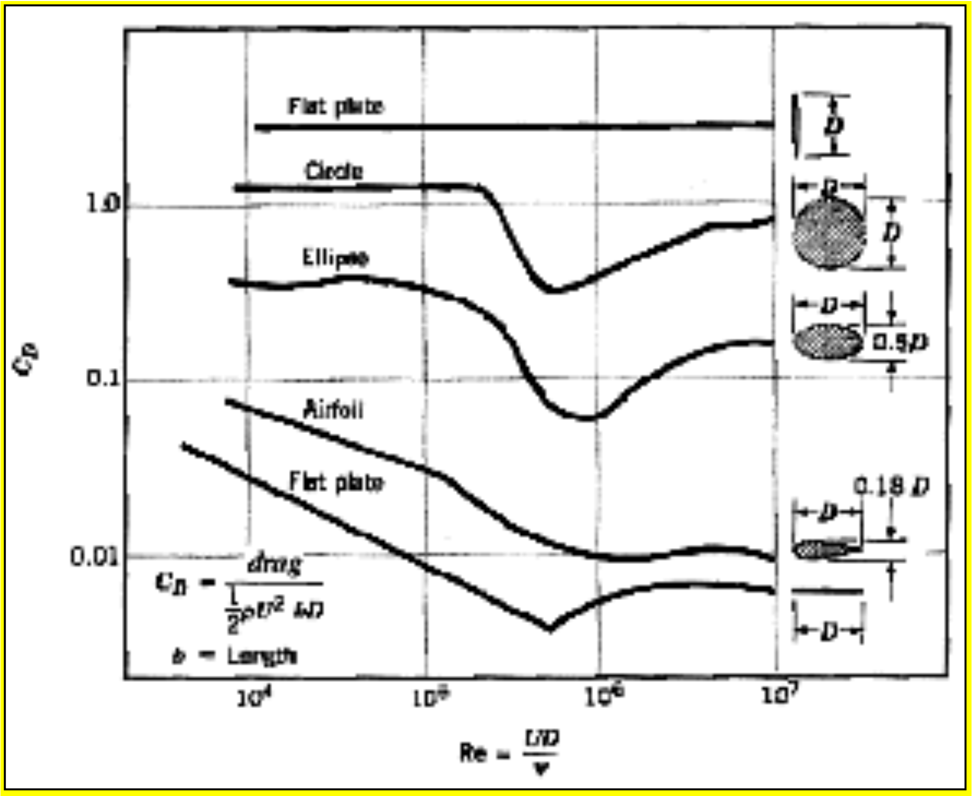


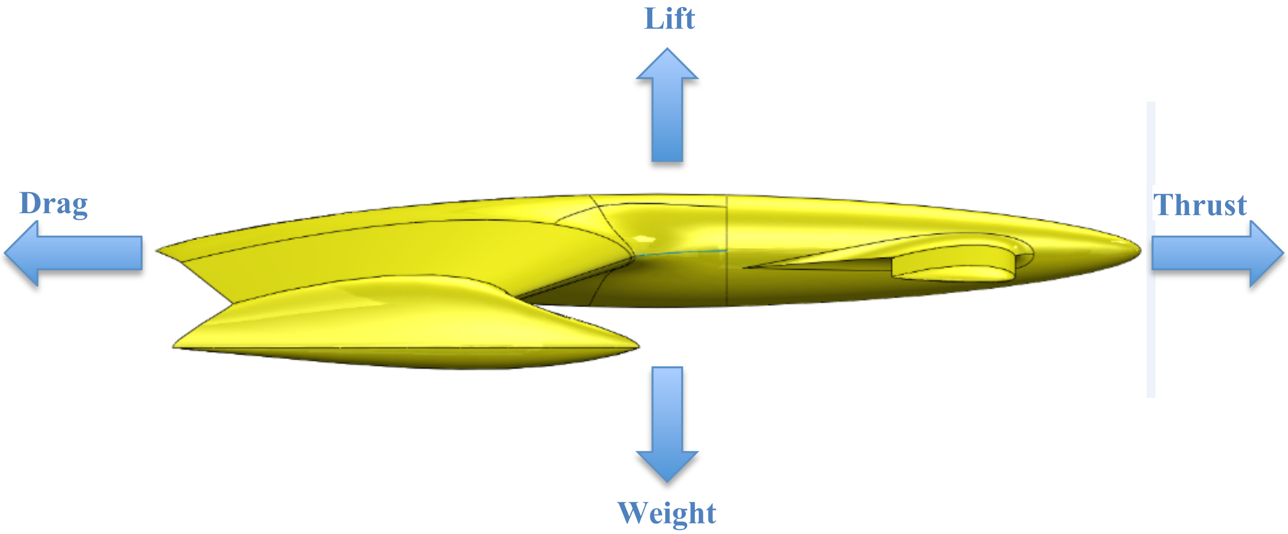
Figure 1.1 Drag and Reynolds Number

The coefficient of drag is predicted implementing an equation using K, the lift dependent component of drag and wing efficiency:

$$C_D = C_{Do} + KC_L^2$$

$$K = 1/\pi ARe_w$$

Assuming steady flight we know thrust is equivalent to drag and lift is equivalent to weight of the AUV.



Specification of a maximum weight for the AUV is one of the primary factors in determining flight performance. As the aircraft flies through the air at high enough speeds, the airfoil shaped wings generates areas of high-pressure and low-pressure regions. Lift is proportional to a non-dimensional coefficient, square of aircraft velocity, surface area, and density of ambient air. Substituting weight for lift, a value for coefficient of lift is determined.

$$C_L = \frac{Weight}{{}^{1}\!/_{2}\rho_a V^2 S} \qquad [2]$$

Based upon these preliminary calculations, the coefficients of drag and lift are used to calculate the drag of the AUV:

$$Drag = C_d q Area \quad \text{where,} \qquad [2]$$

$$q = {}^{1}\!/_{2}\,\rho V^2$$

In order to determine the flight and subsurface performance, the drag values and coefficients of drag were evaluated at a range of velocities and AUV weights.

2.2 Power and Thrust Calculations

Based upon the assumption the AUV is in steady flight, we know drag must be equivalent to the thrust. Calculations were made to look at the required thrust to maintain flight as well as the thrust generated by the motor. These values were calculated for the range of velocities from 1 m/s to 100 m/s. This reveals a flight characteristic showing operating parameters for the AUV.

$$T_{req} = qAC_{d0} + \frac{2KL^2}{\rho_a V^2 A} \qquad [3]$$

$$T_{gen} = \frac{P_{supplied} \cdot \eta}{V} \qquad [1]$$

2.3 Power Requirements

Design for the Shearwater Propulsion system is based around the idea of compromise. This compromise is the understanding that particular instrumentation that may be the most efficient for one component may not be the most efficient or best design for the AUV as a whole. Various components of flight and submersion were analyzed separately to determine flight envelopes.

2.3.1 Climb Performance

Different operations were researched separately to determine power requirements during the different stages of the mission. These calculations are all based upon values at sea level due to the low flight elevations. Based upon drag and thrust calculations for speeds of 1m/s to 45 m/s and using these values we were able to determine the minimum velocity required for take off from the ocean surface. These calculations were repeated for various weights of the AUV to determine the penalties for varying weight. The change in elevation of the aircraft dependent on the velocity is calculated by:

$$\frac{dh}{dt} = \frac{(T - D) \cdot V_a}{W}$$

This information was then graphed to develop a picture of the operation and determine if there is a large affect on the climb performance, or if the supplied power would be great enough to lift the vehicle out of the water.

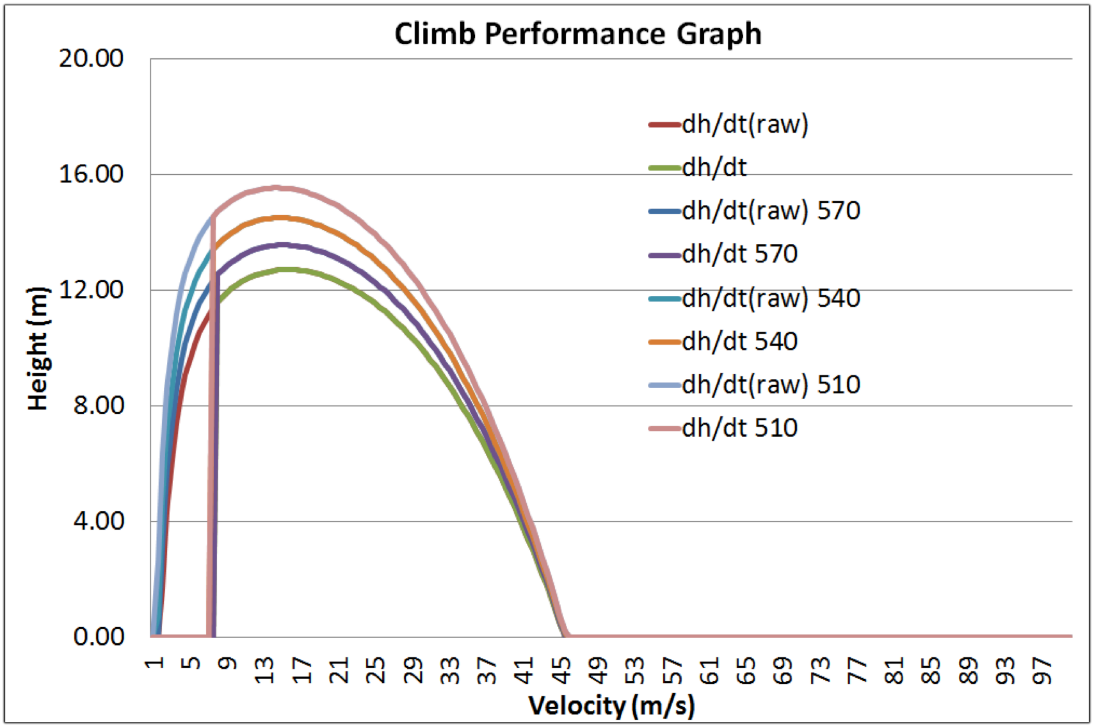


Figure 2.3.1 Steady Climb Performance

This is a visual representation for the effects of weight and velocity on the climb performance. As the graph reveals, the vehicle is able to take off from the ocean as long as a velocity of around 8 m/s is maintained. Ground effect and low flight elevation will provide the lift to sustain flight.

2.3.2 Steady Flight Performance

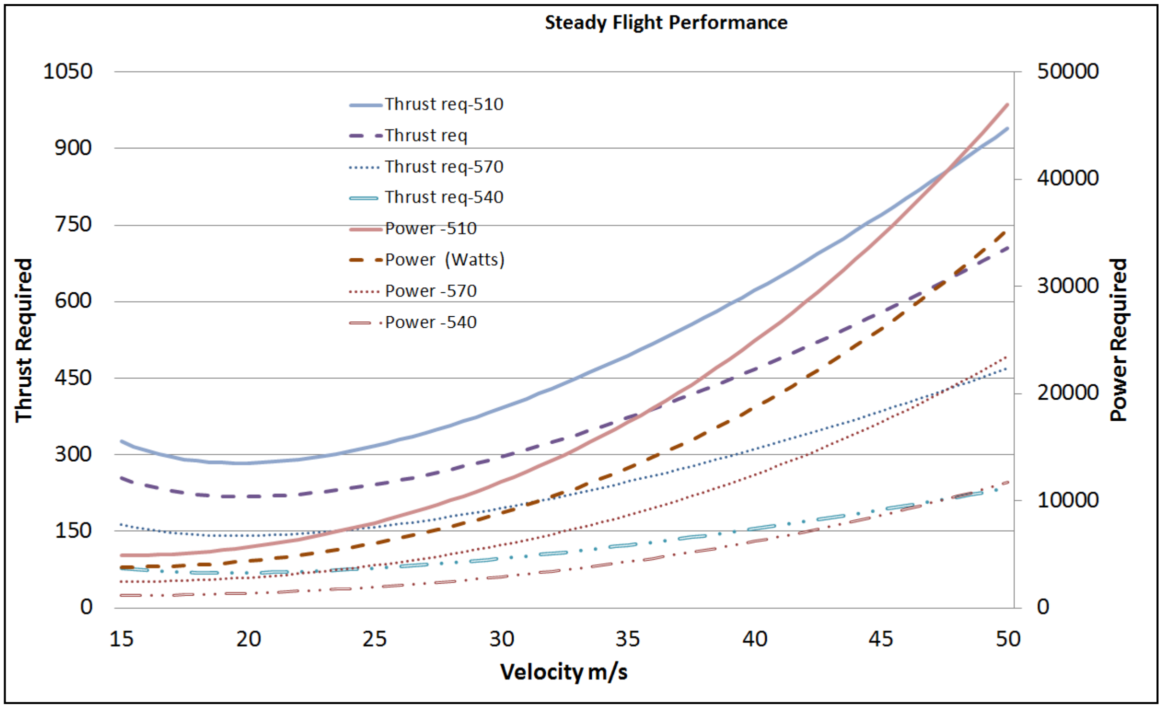


Figure 2.3.2 Steady Flight Performance

2.3.3 Hydrodynamic Operations

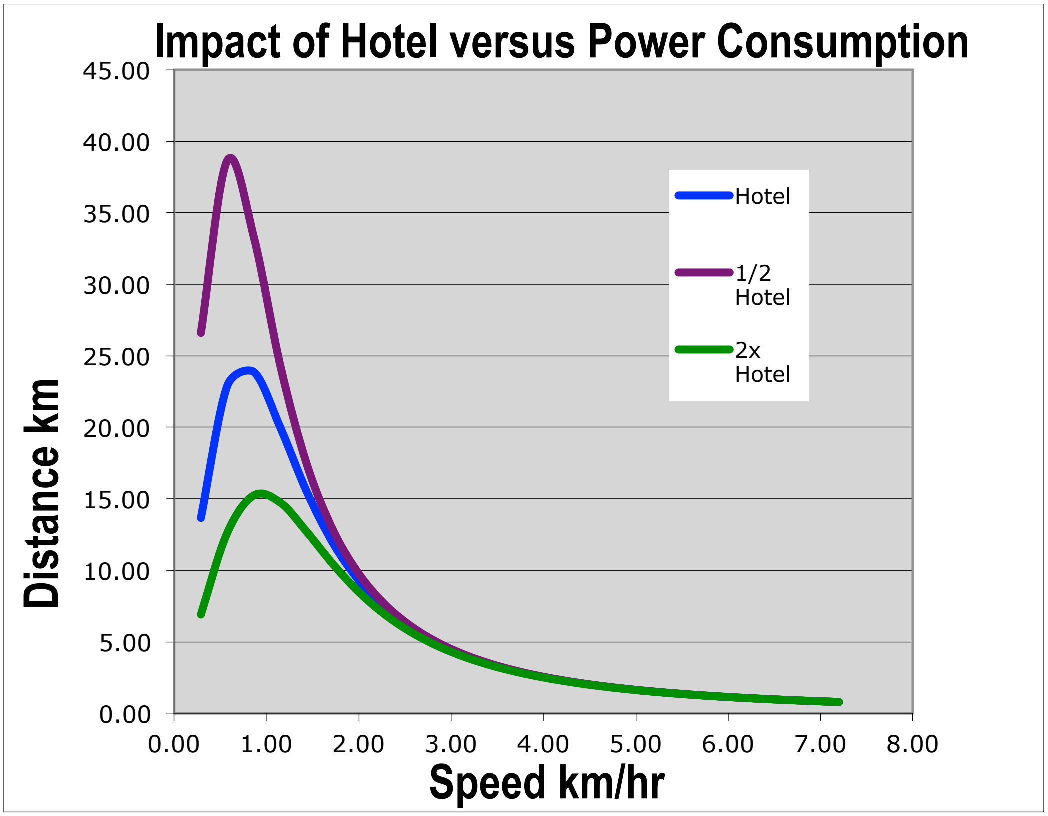


Figure 2.3.3 Hotel versus Power Consumption for Submerged Operations

2.3.4 Total Power

3 Propulsion Alternatives

After developing a picture of the power and propulsion requirements for both hydrodynamic and aerodynamic flight, a suitable motor was chosen. This process involved researching motors that were capable of supplying the right amount of horsepower to the AUV. Based upon preliminary calculations, it was determined that 30 horsepower would be sufficient enough for flight. A variation of motors were considered and included ultralight aircraft motors, motorcycle motors and go kart motors.

3.1 Aerodynamic Flight

Once a few viable motors were chosen a trade table was developed specifying features that were also important for the design of the AUV beyond the power requirements. These trades included the overall weight, the size, the cost, the output and the complexity of each motor. Complexity of the motor was determined by the cooling system of the motor, as well as the fuel type required by the motor. The trade table compared the Kawasaki KLR650, the PRD Fireball 125cc go-kart engine and the Caterpillar C1.5 (T) industrial motor.

Though included in the decision matrix, diesel engines proved to be much too large in dimension and weight for the Shearwater design. Additional specifications considered for the PRD Fireball and the Kawasaki KLR650 during the decision process include:

	Cylinders	**Engine**	**Cooling Type**	**Engine Displacement (cc)**	**RPM**	**Torque (max) (lb-ft)**	**HP**
MOTOR							
PRD Fireball	Single	2 stroke	Liquid	124	15580	NA	28.5
Kawasaki KLR650	4	4 stroke	Liquid	651	5500	36.9	38.6

Table 3.1 Motor Specifications

3.1.1 Ideology

As mentioned, the motor selection for the Aerodynamic flight portion was reduced to include merely three motors and through the use of a decision matrix additional motor characteristics were evaluated for their importance to the AUV design. The characteristics were designated a percentage value of importance and each motor received a ranking from the scale of 1-5 in each category. This was a relatively simple way to compare desirable features for each motor. The decision matrix is included:

Motor	Cost ($)	Weight (kg)	Size (1-5)	Output	Complexity (1-5)	**Totals**
Rating	0.2	0.3	0.2	0.1	0.2	**1**
PRD Fireball	170 (2) **0.4**	19 (1) **0.3**	1 **0.2**	28.5 (2) **0.2**	2 **0.4**	**1.5**
Kawasaki KLR650	6500 (4) **0.8**	54 (3) **0.9**	3 **0.6**	38 (3) **0.3**	3 **0.6**	**3.2**
Caterpillar C1.5 (T)	6000 (4) **0.8**	157 (5) **1.5**	5 **1**	37 (3) **0.3**	3 **0.6**	**4.2**

*The lower the total score, the more optimal motor.

Table 3.1.1 Motor Trade Study

The main deciding factors between the PRD Fireball and the Kawasaki KLR650 are the cost and weight. Based upon performance of the PRD, the Kawasaki motor is also a viable consideration for the propulsion design and would required much of the same information for continued design.

3.1.2 Motor

The PRD Fireball motor is optimal for the Shearwater AUV design based upon the required power output and the low cost and overall size of the motor. The AUV is a relative small diameter and therefore the smaller motor will aid in payload design. For construction, the requirement mention in the PRD 125cc Fireball Engine Manual will need to be followed. The Fuel Oil Ratio of premium grade fuel is 8oz to the gallon (16:1) is one such specification. [4] Gear ratios will need to be determined when a final propeller and transmission are chosen. Additional components are included in the purchase of the motor and include: centrifugal clutch, carburetor with butterfly, electric starter and an exhaust with flex.

Required information includes an in depth analysis of the motor performance and efficiencies. Through real data and testing of the motor the information on peak torque and peak horsepower in comparison to RPMs can be used to determine the rate to run the motor. Ideally, the motor would be run at peak torque during take off and peak horsepower for efficient steady flight. [5] This information is available for many motors, but was not located for the PRD Fireball. This decision must be finalized before the transmission and gear ratios can be determined.

3.2 Hydrodynamic Flight

The focus to rely on existing technologies for the design of the Shearwater allowed the design for submersible propulsion to be based upon the same electric motor as used with the Dorado AUV. Ed Mullinger and Aveox provided information from the time of design. Aveox specializes in Brushless Electric Motors and worked with the Monterey Bay Aquarium Research Institute to customize and design a motor that could be used for the Dorado AUV propulsion system. Based upon the similar size and shape of the Dorado to the Shearwater these brushless motors will be sufficient to maintain submersion.

3.2.1 Engine

Aveox provided a list of potential motors for the Dorado that included electric motors with a large variation of power ratings, max RPM, and load. [Appendix C] The use of brushless motors reduces the potential for being worn out and reduces the noise, which due to the mission scenario and instrumentation is essential. Aveox motors are typically more that 85% efficient while run at half the maximum power and will not require run-in to reach peak performance. This should allow for trustworthy data when being tested. A brushless controller will also need to be used for this propulsion system, otherwise the motor may be damaged. [6]

3.3 Propeller

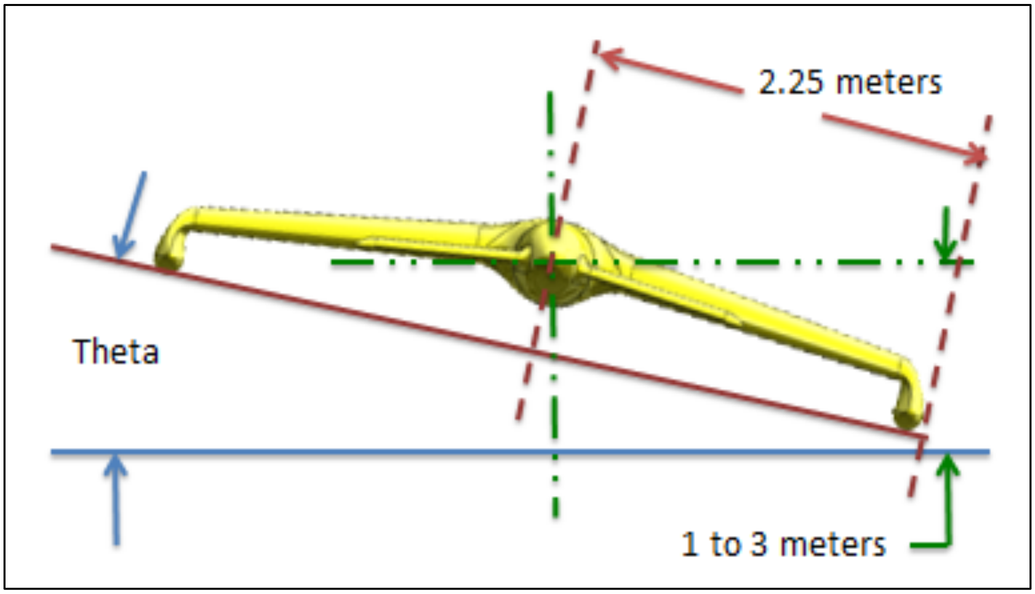
4 Propulsion Suggestions

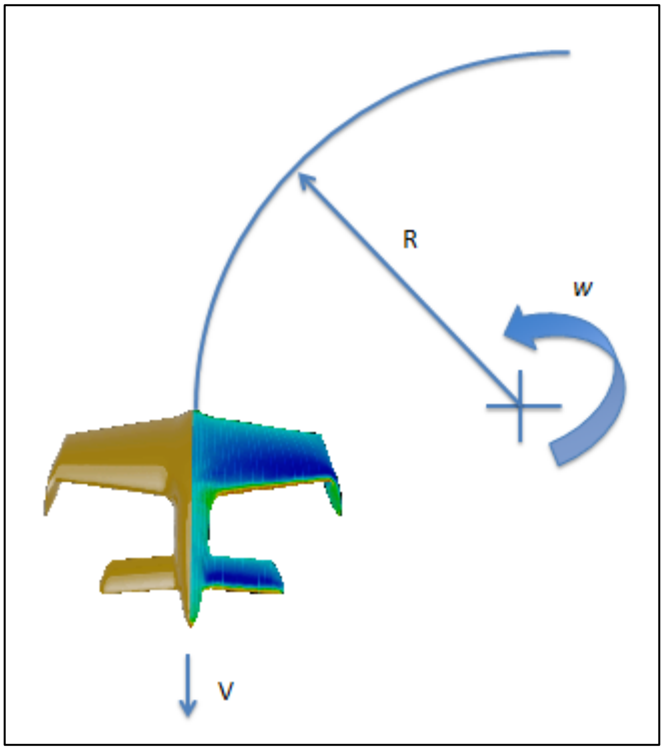
4.1.1 Transmission

The transmission will need to be looked at further depending upon the final motor and propeller configurations dependent upon motor performance.

4.1.2 Turn Calculations

Ground effect takes place when the aircraft is within one wingspans length from the surface of the ocean or ground. The reduction of drag due to ground effect then depends upon what percentage of the wingspan the altitude is for flight. The specified altitude for Shearwater is one half the wingspan or about 2 meters from the surface of the ocean. Based upon this elevation, the maximum tilt angle of the AUV is around 26 degrees if maintaining a distance of one meter from the tip on the wing to the surface. This value was determined through basic geometric calculations.





Based upon calculations to determine the minimum turning radius at various speeds the AUV would be able to turn during flight at a minimum of about 445 meters at a speed of 45 m/s. This value should be considered when designing the obstacle avoidance technology for Shearwater. These are simplistic calculations dependent upon the need for an increase in lift to prevent descent, load factors and angular velocity:

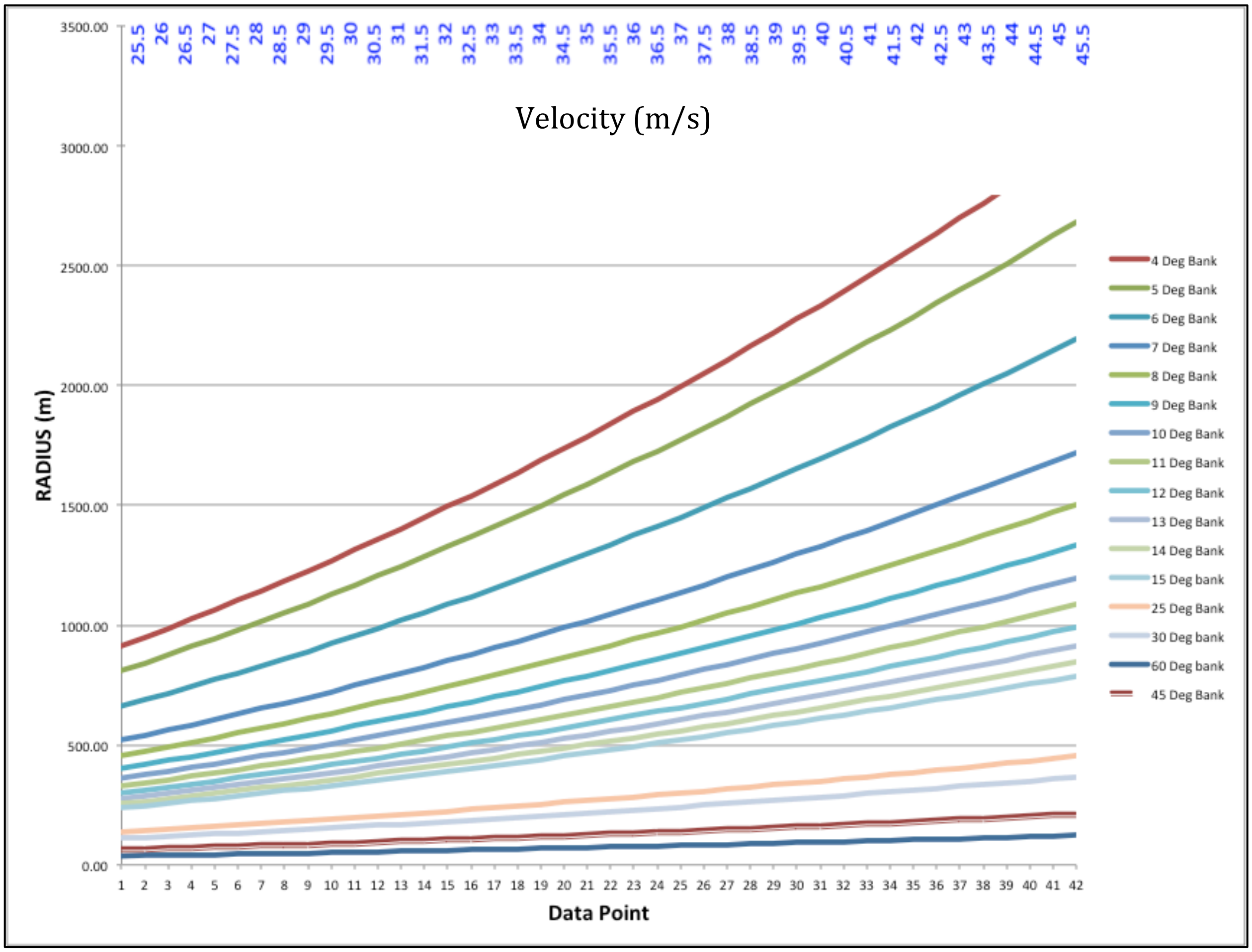
$$^{1}/_{n} = \cos\theta$$

$$C_{L\cdot Turn} = \frac{nW}{^{1}/_{2}\,\rho_a V^2 A}$$

$$R = \frac{V^2}{g}\cdot\cot\theta$$

$$\omega = \frac{V}{R}$$

An increase in flight altitude to three meters would enable the AUV to turn at a steeper angle thereby decreasing the turning radius. This may be needed in order to aid in obstacle avoidance. The following graph evaluates turning radius capability at various velocities and turning angles.


Velocity (m/s)
25.5
26
26.5
27
27.5
28
28.5
29
29.5
30
30.5
31
31.5
32
32.5
33
33.5
34
34.5
35
35.5
36
36.5
37
37.5
38
38.5
39
39.5
40
40.5
41
41.5
42
42.5
43
43.5
44
44.5
45
45.5
RADIUS (m)
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
Data Point
1
2
3
4
5
6
7
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41
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4 Deg Bank
5 Deg Bank
6 Deg Bank
7 Deg Bank
8 Deg Bank
9 Deg Bank
10 Deg Bank
11 Deg Bank
12 Deg Bank
13 Deg Bank
14 Deg Bank
15 Deg bank
25 Deg Bank
30 Deg bank
60 Deg bank
45 Deg Bank

5 Acknowledgments

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6 References

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[6] Aveox