



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **Implementing A Low-Cost Long-Range Unmanned Underwater Vehicle: The SeaDiver Glider**

by

David GASSIER - Jerome REBOLLO - Romain DUMONTEIL  
Supervisors: Don BRUTZMAN, Didier LEANDRI

09 January 2007

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Prepared for: Association for the Development of Teaching and Research Area PACA  
(ADER PACA) BP 67 - 13441 Marseilles Cantini - Cedex 6 (FRANCE)

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# **INSTITUT OF ENGINEERING SCIENCE**

**TOULON, FRANCE**

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Unmanned Underwater Vehicle:  
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This report completed in cooperation with the Modeling, Virtual Environments and Simulation (MOVES) Institute.

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## ABSTRACT

The SeaDiver Glider is an UUV (Unmanned Underwater Vehicle) used for underwater prospecting at a low cost with a long distances coverage ( $\approx 1400$  miles). It moves without propellers by changing its buoyancy with the help of ballast and its hydrodynamics profile reminiscent of a wing (model NACA0022). Ballast inflation makes it raise the surface, ballast deflated make it submerge the bottom. Ballast is positioned in front of its structure in an optimal position to use the lift of its shape. This up-and-down movement is converted into horizontal displacement by the wing-shape of the SeaDiver Glider. It mimics sinusoidal movements from the sea surface down to 300 feet underwater. This vehicle is able to traverse from one point to another without human intervention.

Key terms: autonomous underwater vehicles, sea measurements, silent, low cost.

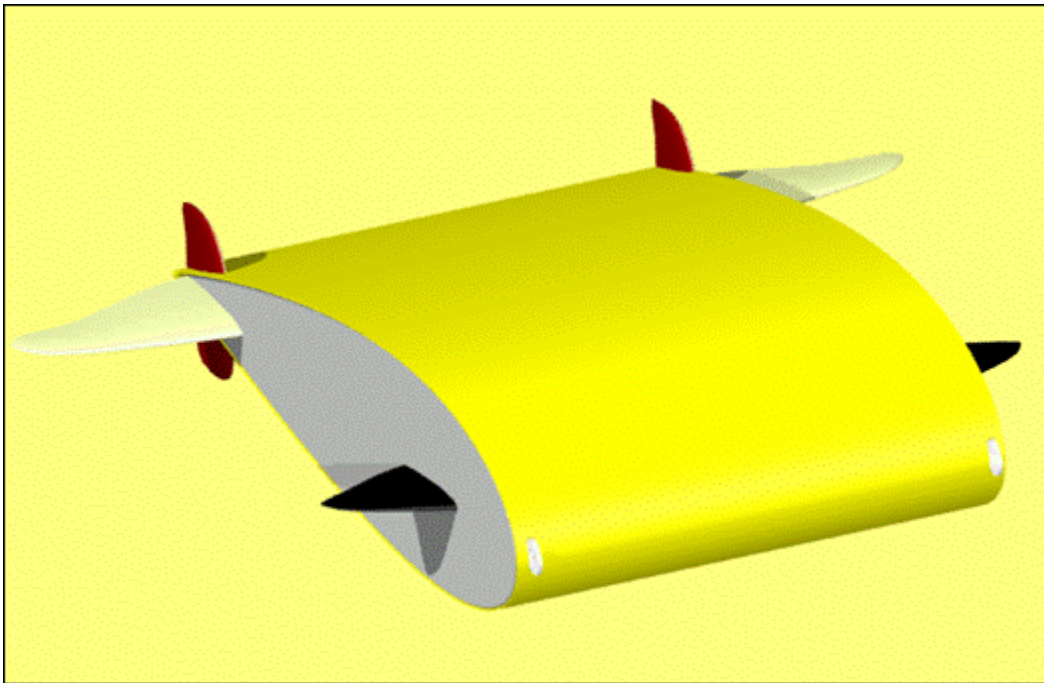


Figure 1. 3D Visualization of the SeaGlider

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# TABLE OF CONTENTS

<b>I.</b>	<b>INTRODUCTION .....</b>	<b>1</b>
<b>II.</b>	<b>PROJECT OVERVIEW .....</b>	<b>3</b>
<b>A.</b>	<b>GENERAL PURPOSE .....</b>	<b>3</b>
<b>B.</b>	<b>CONSTRUCTION .....</b>	<b>4</b>
<b>C.</b>	<b>ADVANTAGE .....</b>	<b>4</b>
<b>III.</b>	<b>THEORY OF THE SEADIVER GLIDER.....</b>	<b>5</b>
<b>A.</b>	<b>COMPUTATION OF THE CENTRE OF BUOYANCY COORDINATES OF THE SEADIVER GLIDER .....</b>	<b>7</b>
<b>B.</b>	<b>SURFACING.....</b>	<b>7</b>
<b>C.</b>	<b>DIVING.....</b>	<b>8</b>
<b>IV.</b>	<b>HYDRODYNAMIC LIMIT OF THE SEADIVER GLIDER .....</b>	<b>9</b>
<b>A.</b>	<b>DEFINITION OF THE SHAPE .....</b>	<b>9</b>
<b>B.</b>	<b>CHARACTERISTICS OF THE OCEAN .....</b>	<b>10</b>
<b>C.</b>	<b>NEEDED PARAMETERS FOR THE LIFT AND DRAG COMPUTATION.....</b>	<b>10</b>
<b>D.</b>	<b>LIFT AND DRAG CALCULATION.....</b>	<b>11</b>
<b>E.</b>	<b>RESULTS .....</b>	<b>12</b>
<b>F.</b>	<b>LIMITATIONS OF THE RESULTS.....</b>	<b>13</b>
<b>V.</b>	<b>SUBSYSTEM DESIGN REQUIREMENTS .....</b>	<b>15</b>
<b>A.</b>	<b>FRAME.....</b>	<b>15</b>
<b>B.</b>	<b>FAIRING SHAPE .....</b>	<b>15</b>
<b>C.</b>	<b>BALLAST .....</b>	<b>15</b>
<b>D.</b>	<b>MANEUVERABILITY AND STABILIZATION .....</b>	<b>16</b>
<b>E.</b>	<b>MANAGEMENT .....</b>	<b>16</b>
<b>VI.</b>	<b>MISSION REQUIREMENTS .....</b>	<b>17</b>
<b>A.</b>	<b>CONSTRAINTS.....</b>	<b>17</b>
<b>B.</b>	<b>AUTONOMOUS .....</b>	<b>17</b>
<b>C.</b>	<b>AUTONOMY .....</b>	<b>17</b>
<b>VII.</b>	<b>MISSIONS PHASES .....</b>	<b>19</b>
<b>A.</b>	<b>SETTING IN WATER AND START .....</b>	<b>19</b>
<b>B.</b>	<b>EXPLORATION, FOLLOWED ITINERARY .....</b>	<b>19</b>
<b>C.</b>	<b>RECOVERY.....</b>	<b>19</b>
<b>D.</b>	<b>SETTING IN WATER AND START .....</b>	<b>19</b>
<b>1.</b>	<b>Placement.....</b>	<b>19</b>
<b>2.</b>	<b>Setting in water .....</b>	<b>19</b>
<b>3.</b>	<b>Diving .....</b>	<b>20</b>
<b>E.</b>	<b>EXPLORATION, FOLLOWED ROUTES.....</b>	<b>20</b>
<b>1.</b>	<b>Navigation.....</b>	<b>20</b>
<b>2.</b>	<b>Guidance .....</b>	<b>20</b>

3.	Piloting .....	20
F.	RECOVERY .....	21
1.	Navigation .....	21
2.	Guidance .....	21
3.	Piloting .....	21
VIII.	POSITION MANAGEMENT .....	23
A.	UNDERWATER POSITIONING .....	24
B.	ESTIMATION OF THE POSITION .....	25
1.	Speed estimation.....	25
2.	Position estimation .....	26
3.	Angular calculation velocity.....	27
4.	Angular calculation position .....	27
5.	GPS measurement.....	28
a.	<i>Distance to arrival</i> .....	28
b.	<i>Course</i> .....	29
6.	Distance to theoretical path (Y).....	29
IX.	POSITION MANAGEMENT SUB SYSTEM .....	31
A.	2 GYROS: .....	31
B.	2 AXIS ACCELEROMETERS: .....	31
C.	GPS: .....	31
X.	AIR BALLAST DEVICE .....	33
XI.	FUTURE WORK: VARIABLE BUOYANCY DEVICE .....	37
XII.	POWER MANAGEMENT .....	41
XIII.	SIMULATION TOOLS: AUV WORKBENCH BY THE MOVES INSTITUTE.....	43
A.	DIFFERENCES WITH THE MODELS ALREADY DONE .....	45
XIV.	CONSTRUCTION DIARY .....	47
A.	DATES .....	47
XV.	CONCLUSION .....	51
	ANNEXES SUMMARY .....	53
	AN INTRODUCTION TO THE AUV WORKBENCH ( <i>SOURCE: AUV WORKBENCH HELP TOPICS</i> ).....	55
	L-3 MEETING REPORT.....	57
	CHARACTERISTICS OF DIFFERENT BATTERIES .....	59
	INITIAL DISTRIBUTION LIST .....	61

## LIST OF FIGURES

Figure 1.	3D Visualization of the SeaGlider .....	iii
Figure 2.	Simplified plan of SeaDiver Glider's underwater behavior showing ballast-driven diving and ascent which in turn leads to forward motion .....	1
Figure 3.	Ballast totally inflated: the SeaDiver Glider surfaces .....	5
Figure 4.	Ballast totally deflated: the SeaDiver Glider dives .....	5
Figure 5.	Centre of buoyancy local place during cycles of diving and surfacing .....	6
Figure 6.	Description of the attack angle $\alpha$ .....	9
Figure 7.	Airfoil Shape of the SeaDiver Glider.....	10
Figure 8.	Lift Force versus Angle of Attack .....	12
Figure 9.	Drag Force versus Angle of Attack .....	13
Figure 10.	Buoyancy Characteristics of the Deployed SeaDiver Glider.....	18
Figure 11.	General diagram of the position management. ....	23
Figure 12.	SeaDiver Glider's main movement.....	24
Figure 13.	Local Coordinate System Defined .....	25
Figure 14.	Angular Positions.....	27
Figure 15.	Position Management Subsystem .....	32
Figure 16.	Diagram of the ballast cycle. ....	33
Figure 17.	Ballast device features .....	34
Figure 18.	Water expansion.....	35
Figure 19.	SeaDiver Glider's ballast. ....	35
Figure 20.	Variable Buoyancy device cycles .....	38
Figure 21.	Diagram of Different States of the Variable Buoyancy Ballast cycles.....	39
Figure 22.	Ballast cycle.....	40
Figure 23.	Screenshot of Multi-panels in the AUV Workbench.....	44

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## LIST OF TABLES

Table 1.	Center of Buoyancy Coordinates of the SeaDiver Glider.....	7
Table 2.	Table of Water Expansion in each Stage of the Ballast Device .....	35
Table 3.	Table of Ballast Stages.....	36

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## I. INTRODUCTION

The SedDiver glider robot is autonomous and silent. It can traverse 700 nautical miles by following a predetermined route. Possibilities offered by SeaDiver Glider are interesting because they allow obtaining different types of measurements like temperature, salinity far away from the shore, cost effective. It is possible to imagine a fleet of SeaDiver Gliders surveying numerous parts of the ocean which are not feasible using boats because of the cost of such missions.

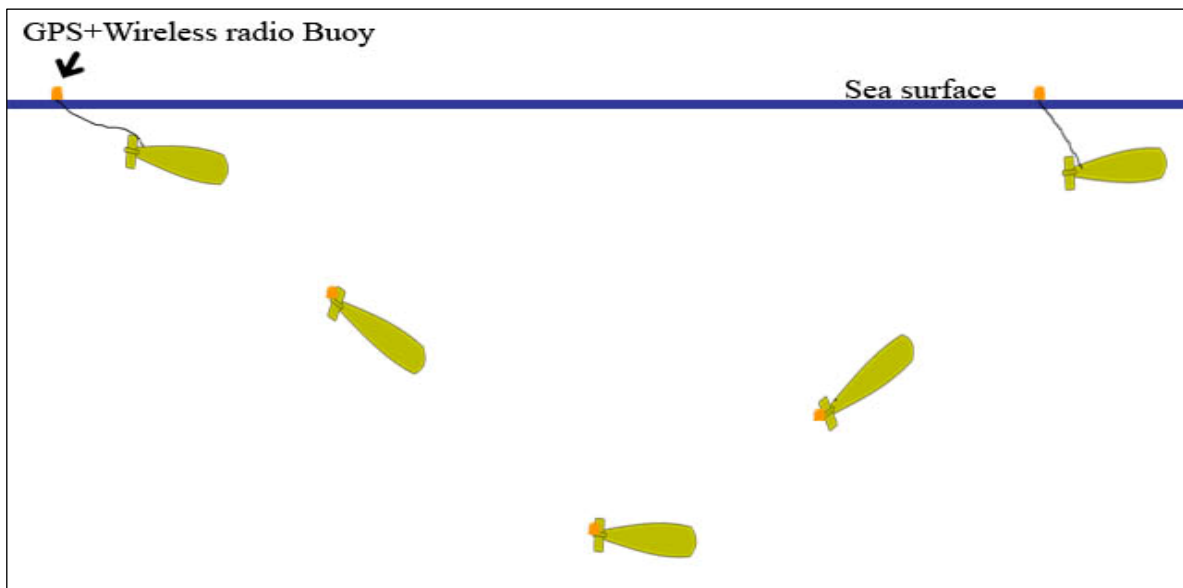


Figure 2. Simplified plan of SeaDiver Glider's underwater behavior showing ballast-driven diving and ascent which in turn leads to forward motion

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## **II. PROJECT OVERVIEW**

This is an ongoing research project conducted in partnership between the I.S.I.T.V. of Toulon (Engineering Superior Institute of Toulon) - Robotics Laboratory and the Center for AUV Research and SAVAGE Labs - Naval Postgraduate School of Monterey, California. All specifications and features are subject to further development.

### **A. GENERAL PURPOSE**

Range:	700 NM
Speed:	1 to 2 knots depending on the sea state
Autonomy:	30 days power supplied by AGM batteries (12 volts, 40 AH) for servos motors and ballast management, and NiMH Batteries (6 volts, 12 AH) for GPS and Inertial Measurement Unit (IMU) module
Memory:	Storage for position and a vast number of waypoints available, storage is also used for communication between SeaDiver Glider and others entity during the mission
Standardized:	Planned: Java is used to control the system. Currently using PICBasic for low-level analog interfaces and vehicle control.
Investigated depth:	100 meters (150 psi) to surface. Minimum of 20 meters of depth to function
Precision:	Good accuracy obtained with a GPS fixes and the IMU device
Accuracy:	< 10 meters immersed and < 5 meters at the surface
Sensors:	-2 axis accelerometer and 2 gyros -20 Channel GPS Module

**B. CONSTRUCTION**

Size (length x width):	64 in x 37 in (1.60 m x 0.80 m)
Minimum weight in air:	165 lbs (75 kg)
Weight in water:	0 lbs in water (due to its buoyancy)

**C. ADVANTAGE**

Autonomy:	30 days in function.
Free space:	Large space to embed systems and payload.
Low cost	Currently \$2000 - \$3000 cost.

### III. THEORY OF THE SEADIVER GLIDER

The difference between the forces applied at the centre of buoyancy (CB) and the centre of gravity (CG) create a positive moment which makes the SeaDiver Glider surface. The SeaDiver Glider uses its lift to push on the water and surfaces with value of attack angle less than  $20^\circ$ .

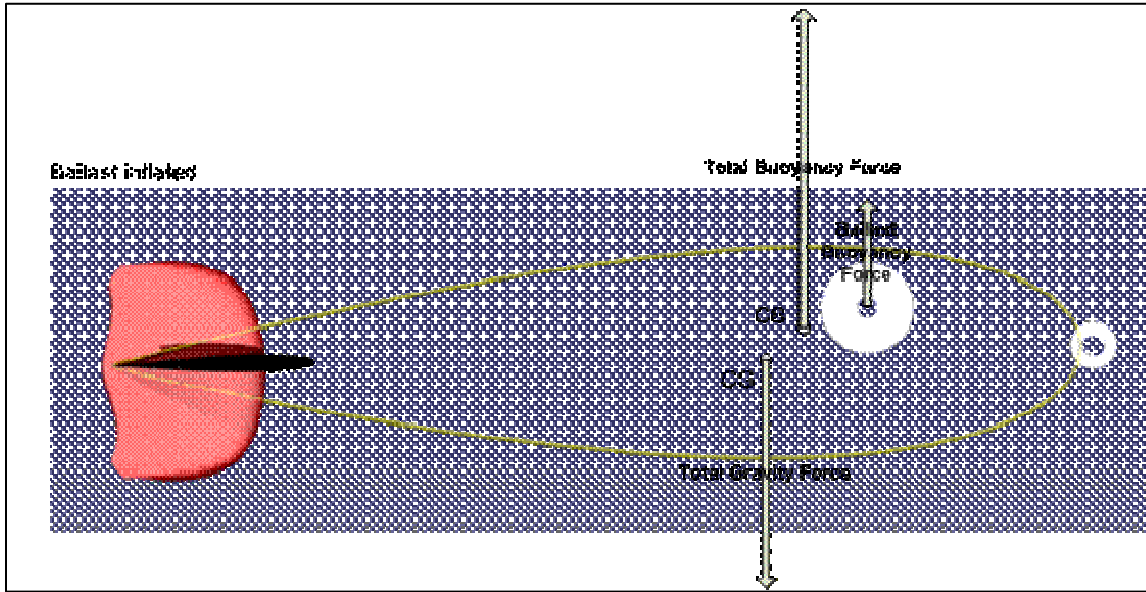


Figure 3. Ballast totally inflated: the SeaDiver Glider surfaces

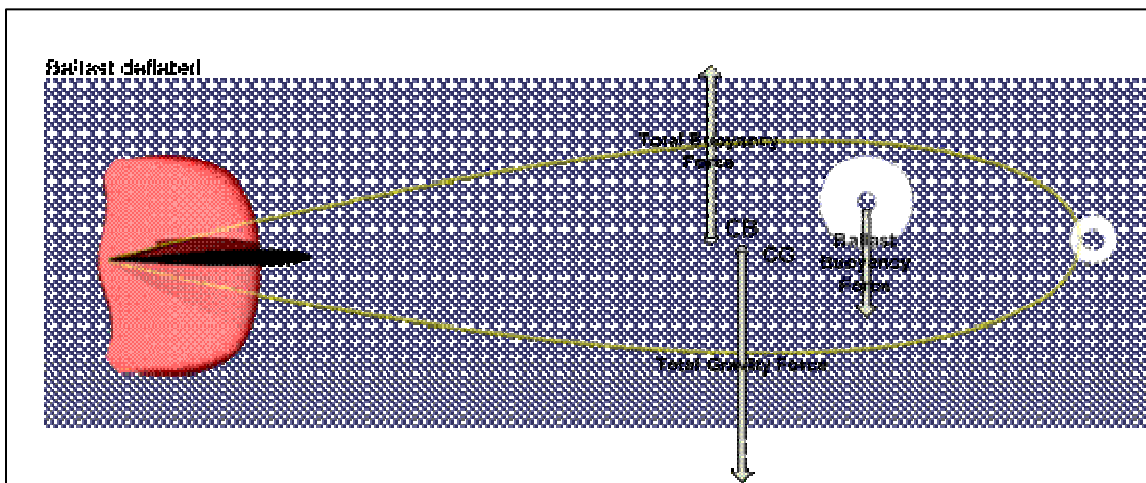


Figure 4. Ballast totally deflated : the SeaDiver Glider dives

The difference between the forces applied at the center of buoyancy (CB) and the centre of gravity (CG) create a negative moment which makes the SeaDiver Glider dive. The SeaDiver Glider uses its lift to push on the water and dives with value of attack angle more than  $-20^\circ$ .

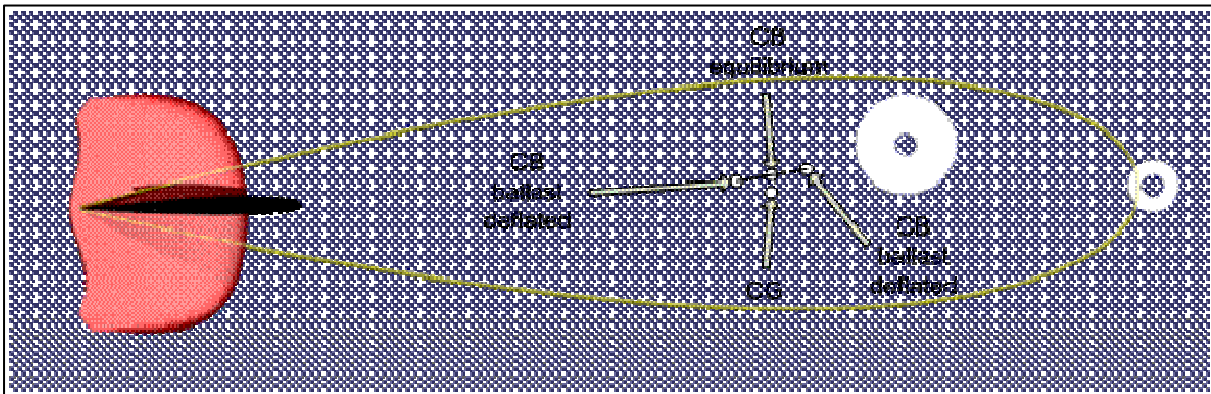


Figure 5. Centre of buoyancy local place during cycles of diving and surfacing

Figures 4 and 5 show the location of the centre of buoyancy when the ballast is inflated and when it is deflated.



## A. COMPUTATION OF THE CENTRE OF BUOYANCY COORDINATES OF THE SEADIVER GLIDER

$x_{equilibrium\_CB}$	x coordinate of the CB
$y_{equilibrium\_CB}$	y coordinate of the CB
$z_{equilibrium\_CB}$	z coordinate of the CB
$x_{ballast}$	x coordinate of the application of the ballast buoyancy force
$y_{ballast}$	y coordinate of the application of the ballast buoyancy force
$z_{ballast}$	z coordinate of the application of the ballast buoyancy force
$x_{variable\_CB}$	new x coordinate of the CB
$y_{variable\_CB}$	new y coordinate of the CB
$z_{variable\_CB}$	new z coordinate of the CB
$initial\_buoyancy$	Buoyancy of the SeaDiver Glider
$ballast\_buoyancy$	Buoyancy of the ballast
$\theta$	attack angle of the SeaDiver Glider

Table 1. Center of Buoyancy Coordinates of the SeaDiver Glider

## B. SURFACING

Ballast inflated  $\theta$  is  $> 0$ :

$$x_{variable\_CB} = \frac{initial\_buoyancy \times x_{equilibrium\_CB} + \cos(\theta) \times (x_{ballast} - x_{equilibrium\_CB}) \times ballast\_buoyancy}{initial\_buoyancy + ballast\_buoyancy}$$

$$y_{variable\_CB} = y_{equilibrium\_CB}$$

$$z_{variable\_CB} = \frac{initial\_buoyancy \times z_{equilibrium\_CB} + \sin(\theta) \times (z_{ballast} - z_{equilibrium\_CB}) \times ballast\_buoyancy}{initial\_buoyancy + ballast\_buoyancy}$$

### C. DIVING

Ballast deflated  $\theta$  is  $< 0$ :

$$x_{variable\_CB} = \frac{initial\_buoyancy \times x_{equilibrium\_CB} - \cos(\theta) \times (x_{ballast} - x_{equilibrium\_CB}) \times ballast\_buoyancy}{initial\_buoyancy - ballast\_buoyancy}$$

$$y_{variable\_CB} = y_{equilibrium\_CB}$$

$$z_{variable\_CB} = \frac{initial\_buoyancy \times z_{equilibrium\_CB} - \sin(\theta) \times (z_{ballast} - z_{equilibrium\_CB}) \times ballast\_buoyancy}{initial\_buoyancy - ballast\_buoyancy}$$

Each set of equations are basically a barycentre calculation of two forces with computed using the weight associated with each force.

#### IV. HYDRODYNAMIC LIMIT OF THE SEADIVER GLIDER

The goal of this part is to define the attack angle, the drag and the lift of the SeaDiver Glider shape. In the following diagram, the black arrow represents the direction of the fluid flow.

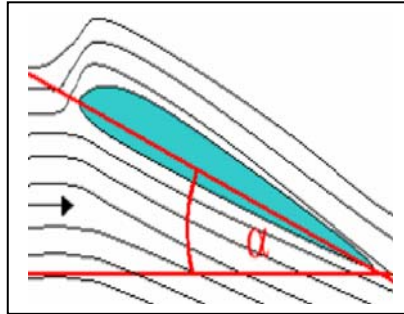


Figure 6. Description of the attack angle  $\alpha$

##### A. DEFINITION OF THE SHAPE

The SeaDiver Glider profile is made with a NACA0022 airfoil shape from the NASA (National Aeronautics and Space Administration).

The four digits 0022 are described:

1. **One digit** describing maximum camber as percentage of the chord.
2. **One digit** describing the distance of maximum camber from the airfoil leading edge in tens of percents of the chord.
3. **Two digits** describing maximum thickness of the airfoil as percent of the chord.

So **NACA 0022** airfoil is symmetrical, the 00 indicating that it has no camber. The 22 indicates that the airfoil has a 22% thickness to chord length ratio: it is 22% as thick as it is long.

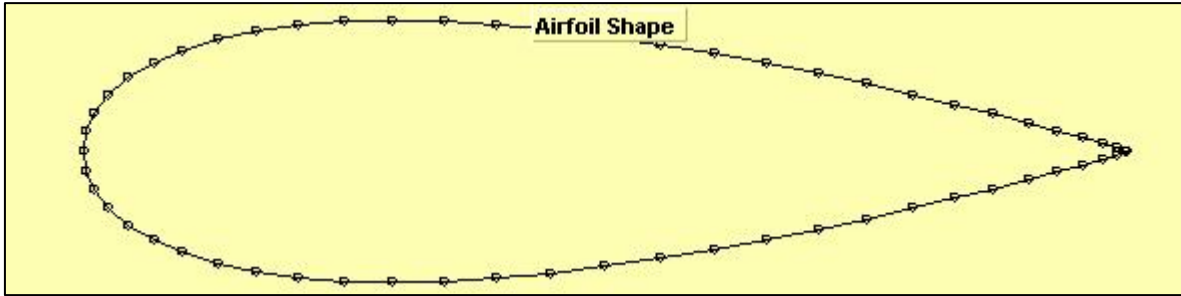


Figure 7. Airfoil Shape of the SeaDiver Glider.

Length of the currently built SeaDiver Glider is: 1.60m (63")

Width of the currently built SeaDiver Glider is: 0.80m (31.5")

## B. CHARACTERISTICS OF THE OCEAN

In order to calculate a typical attack angle (ratio between lift and drag optimum), ocean characteristics are assumed to have the following values:

- Density of salt water =  $1190 \text{ kg.m}^{-3}$
- Speed of sound in salt water =  $1500.29 \text{ m.s}^{-1}$
- Kinematics viscosity with an ocean at  $12.5^{\circ}\text{C}$  =  $12.245 * 10^{-7} \text{ m}^2.\text{s}^{-1}$

## C. NEEDED PARAMETERS FOR THE LIFT AND DRAG COMPUTATION

$$\text{Reynolds's number: } Re = \frac{(v_{\infty} \times l)}{\nu} \approx 65000$$

$$v_{\infty} = \text{velocity of vehicle in the fluid} = 1 \text{ m.s}^{-1}$$

$$l = \text{characteristic length of the wing} = 1.60\text{m}$$

$$\nu = \text{kinematics viscosity} = 12.245 \times 10^{-7} \text{ m}^2.\text{s}^{-1}$$

#### D. LIFT AND DRAG CALCULATION

There are 2 steps in the lift and drag calculation. Lift and drag coefficients depend on the attack angle of the SeaDiver Glider. The range of the attack angle used is:  $\pm 25^\circ$ . To obtain these coefficients, NASA performed experiments in their laboratory and recorded the result in tables located here:

<http://virtualskies.arc.nasa.gov/aeronautics/tutorial/calculating.html>

The formula which links lift and drag coefficients (and corresponding lift and drag forces) are:

$$L = C_L \times \rho \times \frac{V^2}{2} \times A$$

**L** is the lift force (N: Newton)

**C<sub>L</sub>** is the coefficient of lift

**ρ** is the density of the fluid (1190 kg/m<sup>3</sup>)

**V** is the velocity of the object relative to the fluid (1 or 2 knots pending test result)

**A** is the surface area of the lifting surface

$$F_x = \frac{1}{2} C_x(Re, \theta) \times \rho \times A \times V^2$$

**F<sub>x</sub>** is the drag force (N: Newton)

**C<sub>x</sub>** is the coefficient of drag (a dimensionless constant) in function of the number of Reynolds and the number of Mach

**ρ** is the density of the fluid (1190 kg.m<sup>-3</sup>)

**A** is the reference area (frontal surface: 0.347\*0.81 in m<sup>2</sup>)

**v** is the velocity of the object relative to the fluid (1 or 2 pending result )

## E. RESULTS

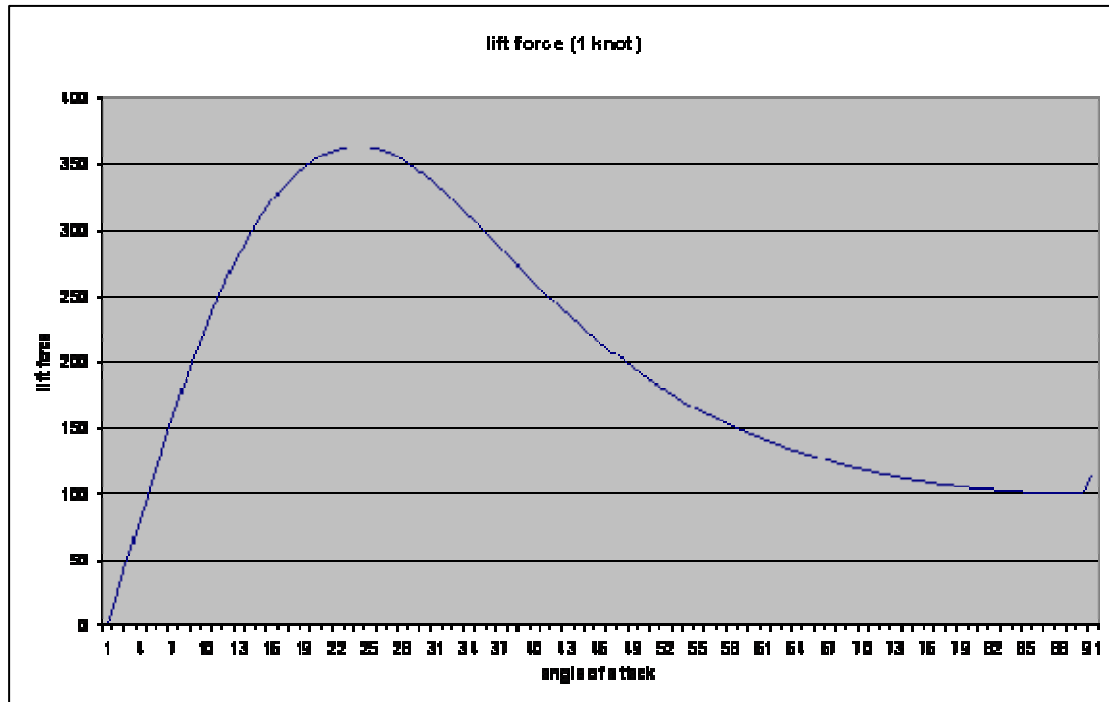


Figure 8. Lift Force versus Angle of Attack

This diagram shows that the maximum lift force is for an attack angle in the range of  $19^{\circ}$  to  $25^{\circ}$  so with the effect of the fins and the safety margin,  $20^{\circ}$  of attack angle will be optimum. It corresponds to 358 N of lift force.

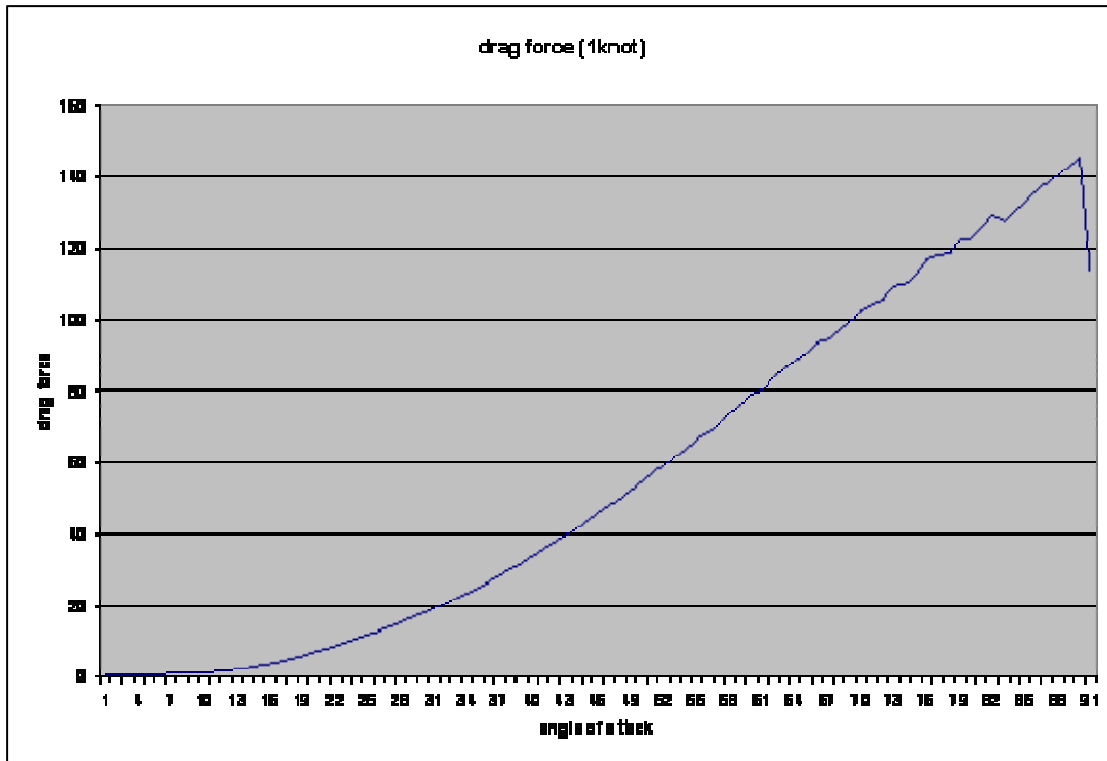


Figure 9. Drag Force versus Angle of Attack

The drag force at 20° attack angle is not as strong ( $F_x = 7.9 \text{ N}$ ). It confirms the optimum value of the attack angle.

The vehicle will therefore have an optimum angle of attack oscillating between -20 degrees and 20 degrees in order to have the best possible propulsion force in water.

## F. LIMITATIONS OF THE RESULTS

The software used does not model laminar separation bubbles and flow separation, so the computed results will be incorrect if either of these effects occur. With a 1 to 2 knots speed, such drag effects won't happen.

Flow separation, as it occurs at stall, is modeled to some extent by empirical corrections, so that maximum lift can be predicted for "conventional" airfoils.

It is questionable whether two dimensional analysis methods can be used with sufficient accuracy in this regime, as the flow field beyond stall is fully three dimensional with span-wise flow and strong vortices.

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## **V. SUBSYSTEM DESIGN REQUIREMENTS**

For this type of vehicle, it is important to define all sub systems and fields of studies. The best way to find solutions for a project is to talk with specialist. The feasibility of an idea must be discussed physically during meetings with people. Extensive engineering efforts and discussions are behind this design.

### **A. FRAME**

The frame of SeaDiver Glider must be able to maintain the hydrodynamic envelope and at the same time all the embedded equipments.

The primary frame parameter to define is: the type of material to be used according to the material density (which must be close to the water), of the hardness and porosity and the ability of the material to be shaped.

### **B. FAIRING SHAPE**

An airfoil profile is used. Performances of the NACA0022 are known and can be found in the NASA archive:

[http://ceani.ulpgc.es/ingenetcd/testcases/aeronautics/t5210/\(CFD-CEM\)%20Airfoil%20Design.htm](http://ceani.ulpgc.es/ingenetcd/testcases/aeronautics/t5210/(CFD-CEM)%20Airfoil%20Design.htm)

### **C. BALLAST**

Several technical solutions can be appropriate. A pneumatic air-displacement is used, which is less expensive and easier to set up but obviously more sensitive to pressure problems at great depths than an oil-based system. The movable fixed ballast includes 3~4 kg of weight transfer. Consideration of free space is important so the movable ballast will need 5 times more space than the air system.

Another design possibility is to move oil from the hull to the water, which would have the advantage of not taking account of the pressure and having a stable volume even if the pressure changes a lot. This design option was rejected based on cost and inability to replenish hydraulic fluid in a small system.

#### **D. MANEUVERABILITY AND STABILIZATION**

6 planes surfaces are included in the SeaGlider design.

-2 fixable fins for the stability.

-2 moving horizontal planes astern

-2 smaller horizontal lateral planes close to the center of buoyancy.

The SeaDiver Glider is able to accomplish a  $60^\circ$  angle when maneuvering though one dive or rise period.

To U-turn ( $180^\circ$ ) the SeaDiver Glider uses three cycles (one dive and two rises or two dives and one rise).

#### **E. MANAGEMENT**

System management is accomplished via electronic control (more detail in Chapter IX). Still, there is an interest to divide this system into sub systems. Indeed the various parts to be managed are:

- Planes and stability
- Ballast management
- GPS and IMU (Inertial Motion Unit)
- Batteries

The SeaDiver Glider provides its position to the embedded system with a serial link.

## **VI. MISSION REQUIREMENTS**

This chapter summarizes SeaDiver Glider mission requirements. Indeed this type of UUV glider is at the beginning of its development, so not many usable standards are available. Some expensive systems are already made and are on the market.

Dealing with physical constraints to achieve realistic mission requirements needs to produce the simplest, most reliable and economic solution.

### **A. CONSTRAINTS**

Maximum depth:

- 100m (300 feet) corresponds to 10 bars ( $\approx 150$  psi) of pressure.
- The dry box needs to be strong enough to go at 100m.

### **B. AUTONOMOUS**

- Navigation of the robot at the surface and underwater.

GPS at the surface and an Inertial Motion Unit (IMU) with wireless sensors underwater estimate the position in 3 dimensions.

### **C. AUTONOMY**

SeaDiver Glider must be able to decrease and increase its buoyant volume in a linear way to increase stability. Diving and surfacing phases need to have the same speed to have a save power. If not, this will increase energy consumption and reduce the autonomy of the robot. The goal is to use the less energy possible for the ballast controls during the linear phases (diving or surfacing). The bladder has to resist the air expansion from a 0~1 bar pressure differential to a 10~11 bars pressure differential summarized in the following figure.

At the 100m
Sea pressure: 10~11 bars. Ballast pressure: > 11 bars (to enable the inflation of the tank). Volume: 3.96 liters = 1 gallons <b>Pressure differential Ballast/Sea: 0~1 bar.</b>
Near the surface
Sea pressure: 1~2 bars Ballast pressure: > 15 bars Volume: 3.96 liters = 1 gallons <b>Pressure differential Ballast/Sea: 15 bars</b>

Figure 10. Buoyancy Characteristics of the Deployed SeaDiver Glider

## **VII. MISSIONS PHASES**

### **A. SETTING IN WATER AND START**

The SeaDiver Glider must be put in the water from a boat or possibly start from a "docking garage". Minimum of 130 feet of depth is required to be efficient. The boat reaches the mission area and deploys the SeaDiver Glider. Before the SeaDiver Glider starts by deflating the air tank, then it initializes its waypoints and the cap needed to be followed to do the mission.

### **B. EXPLORATION, FOLLOWED ITINERARY**

The "navigation device" allows the SeaDiver Glider to know its position under the sea. Position is known with its 2 axis accelerometer, 2 gyros and a GPS at the surface.

### **C. RECOVERY**

Go at the surface, take a GPS fix. A signal is transmitted by its radio with the GPS position of the SeaDiver Glider.

Future work: return to the docking box, recharge the power battery and go for another mission.

The end waypoint is called recovery point.

### **D. SETTING IN WATER AND START**

Procedure to deploy the SeaDiver Glider from a boat: the entire mission is set up in the SeaDiver Glider's memory during pre-mission configuration and verified by testing on a workbench first.

#### **1. Placement**

The boat must be in an area with a minimum depth of 130 feet to allow the sinusoidal path of the robot.

#### **2. Setting in water**

After the SeaDiver Glider has initialized, it inflates its front ballast to stay at the surface. When it is set free in the water it will stabilize via its plate, take a last waypoint to calculate the path to reach the next waypoint, then deflate the front ballast to dive.

### 3. Diving

The SeaDiver Glider dives at a 20-30 degree slope with a speed between 1 and 3 knots. Two moving fins allow directional change to steer a straight path to the next route which was calculated with the last waypoint obtained and the next that must be reached from memory.

Around the next way point, when its sinusoid reaches the surface, another GPS fix is obtained and the dive cycle/surface cycle continues.

The navigation station helps it to reach the next waypoint and follow its route under the sea.

## E. EXPLORATION, FOLLOWED ROUTES

### 1. Navigation

- The SeaDiver Glider collects information about its environment with different sensors:
- 2 axis accelerometers  $\rightarrow$  X, Z **estimation**
- 2 gyroscopes (angular sensors)  $\rightarrow$   $\alpha$ ,  $\beta$  **estimation**
- GPS fix resets X and Y estimation

### 2. Guidance

The SeaDiver Glider follows its mission using routines of position control to stay on its way. It can use undershoot or overshoot normal diving curves in order to adapt to non periodic increments, all under **periodic** controls of the GPS.

### 3. Piloting

Internal side ballasts correct the roll angle. In moving batteries laterally the SeaDiver Glider could also control the roll angle. This other system could be used without overweight.

Classic servo-motors may be used to control the fins.

Activation of the compressor allows the ballast to inflate or deflate which in turn provides a moment force between centre of gravity and centre of buoyancy. The SeaDiver Glider wing shape pushes up or down through the water so the vehicle moves forward.

## **F. RECOVERY**

### **1. Navigation**

The SeaDiver Glider arrives to its recovery point:

**X, Y, Z estimation = X, Y, Z recovery point**

### **2. Guidance**

- Raises the surface and activates a beacon.
- Comes down to sleep during a period.
- Reaches the Docking box.

### **3. Piloting**

Same as the exploration

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## VIII. POSITION MANAGEMENT

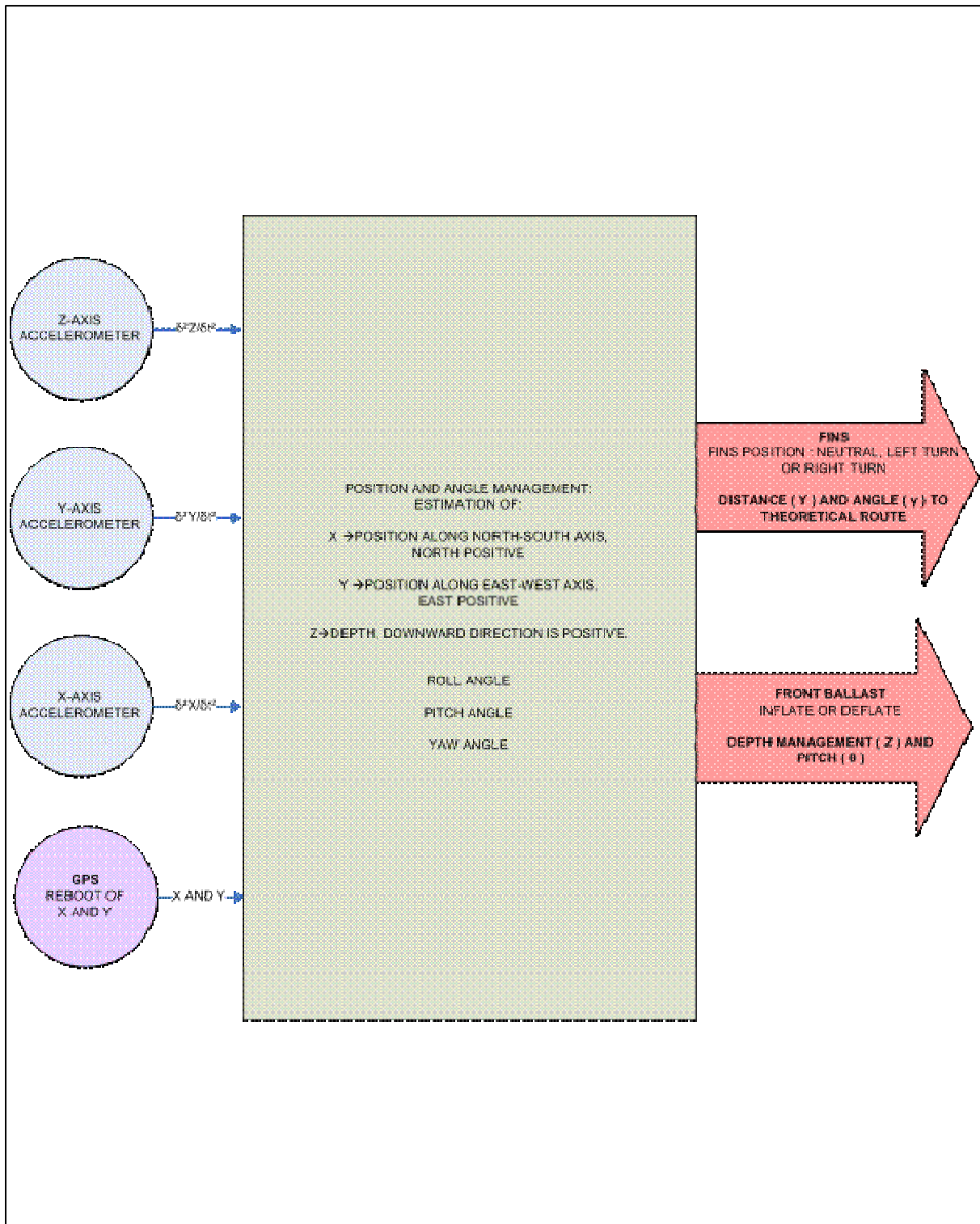


Figure 11. General diagram of the position management.

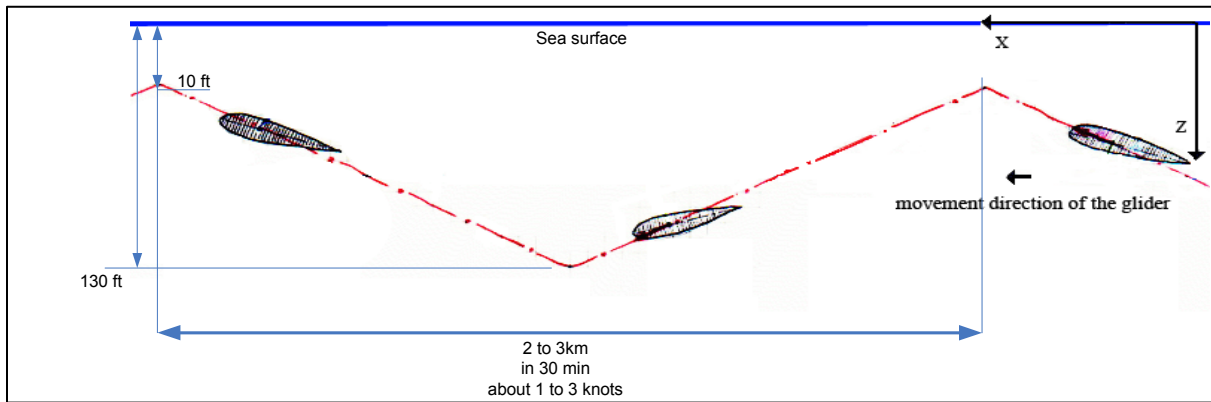


Figure 12. SeaDiver Glider's main movement

#### A. UNDERWATER POSITIONING

X Axis → path, theoretical route.

Y Axis → Distance from the theoretical route.

Z Axis → Depth increase with the depth.

The SeaDiver Glider's theoretical route is a line following X and with  $Y=0$ .

## B. ESTIMATION OF THE POSITION

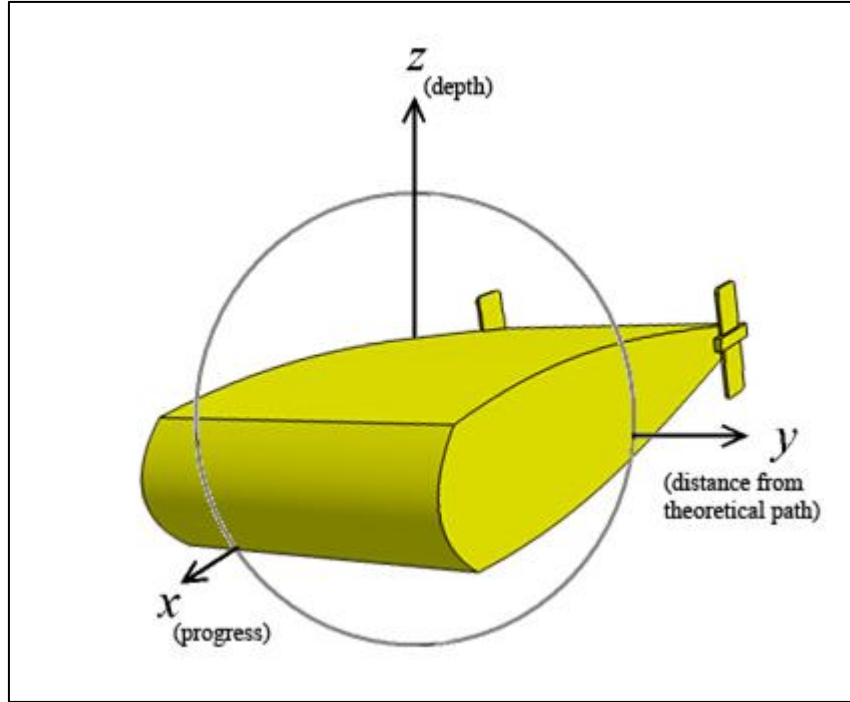


Figure 13. Local Coordinate System Defined

To obtain the speed variation during a  $T1$  period, one method is to measure the acceleration of the three axes every  $P1$  second(s). The sum of these accelerations during  $T1$  seconds shows the global evolution of the speed during  $T1$  seconds. We obtain  $T1/P1$  acceleration summation and values of  $T1$  and  $P1$  depend on the precision required.

### 1. Speed estimation

Every  $p1$  seconds, we measure the 3 acceleration values with the 3 accelerometers. After  $T1$  seconds, we get an estimation of the speed modification in 3 dimensions:

$$\sum_{i=1}^{\frac{T1}{P1}} ax[i] = vx[j] \rightarrow vx[j] = vx[j] + vx[j-1]$$

$$\sum_{i=k*(\frac{T1}{T1}-1)}^{j*\frac{T1}{T1}} ax[i] = vx[j] \rightarrow vx[j] = vx[j] + vx[j-1]$$

$$\sum_{i=k*(\frac{T1}{T1}-1)}^{j*\frac{T1}{T1}} az[i] = vz[j] \rightarrow vz[j] = vz[j] + vz[j-1]$$

$$v[j] = \sqrt{(vx[j])^2 + (vy[j])^2 + (vz[j])^2} = \text{speed at time } j * T1$$

## 2. Position estimation

Every  $T1$  seconds, we obtain the speed modification. After  $T2$  seconds, we calculate the evolution of the position.

$$\sum_{j=k*(\frac{T2}{T1}-1)}^{k*\frac{T2}{T1}} vx[j] = x[k] \rightarrow x[k] = x[k] + vx[k-1]$$

$$\sum_{j=k*(\frac{T2}{T1}-1)}^{k*\frac{T2}{T1}} vy[j] = y[k] \rightarrow y[k] = y[k] + vy[k-1]$$

$$\sum_{i=k*(\frac{T2}{T1}-1)}^{k*\frac{T2}{T1}} vz[j] = z[k] \rightarrow z[k] = z[k] + vz[k-1]$$

This calculation is made until the SeaDiver Glider reaches the surface even though we know its exact GPS position. We collect all the accelerations, speed and position values into a specific memory.

**$x[k]$ ,  $y[k]$  and  $z[k]$  are the coordinates of the SeaDiver Glider at  $k*T2$  into the XYZ marks**

This method estimates the 3D position of the SeaDiver Glider under the sea.

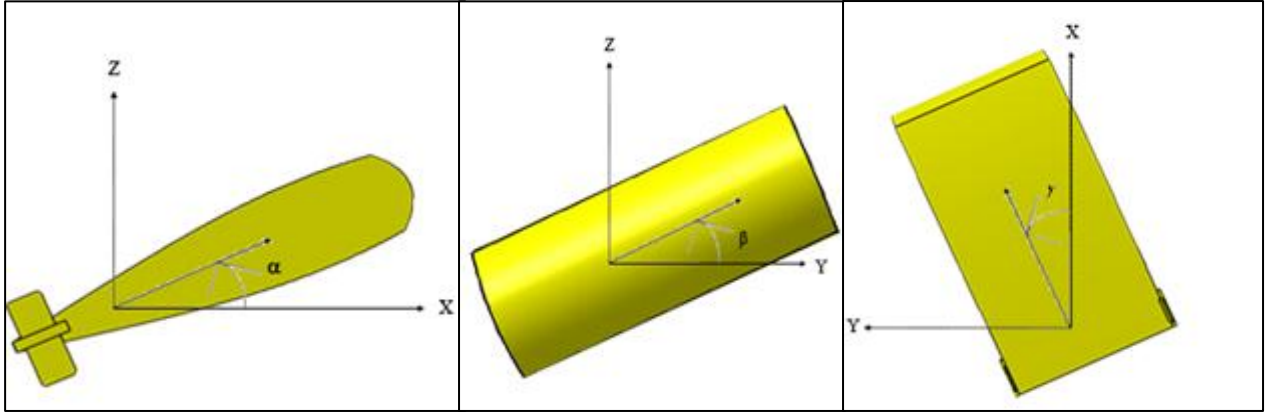


Figure 14. Angular Positions

### 3. Angular calculation velocity

As before, every  $T1$  seconds, we measure the angular acceleration with the 3 gyroscopes. After  $T1$  seconds, we calculate speed modification:

$$\sum_{i=1}^{j \cdot \frac{T1}{p1}} a\alpha[i] = v\alpha[j] \rightarrow v\alpha[j] = v\alpha[j] + v\alpha[j-1]$$

$$\sum_{i=1}^{j \cdot \frac{T1}{p1}} a\beta[i] = v\beta[j] \rightarrow v\beta[j] = v\beta[j] + v\beta[j-1]$$

$$\sum_{i=1}^{j \cdot \frac{T1}{p1}} a\gamma[i] = v\gamma[j] \rightarrow v\gamma[j] = v\gamma[j] + v\gamma[j-1]$$

### 4. Angular calculation position

Every  $T1$  seconds, we got speed modification. After  $T2$  seconds, we calculate the evolution of the position.

$$\sum_{j=1}^{k \cdot \frac{T2}{T1}} v\alpha[j] = \alpha[k] \rightarrow \alpha[k] = \alpha[k] + \alpha[k-1]$$

$$\sum_{j=k*(\frac{T_2}{T_1}-1)}^{k*\frac{T_2}{T_1}} \nu \beta[j] = \beta[k] \rightarrow \beta[k] = \beta[k] + \beta[k-1]$$

$$\sum_{j=k*(\frac{T_2}{T_1}-1)}^{k*\frac{T_2}{T_1}} \nu \gamma[j] = \gamma[k] \rightarrow \gamma[k] = \gamma[k] + \gamma[k-1]$$

$\alpha [k]$ ,  $\beta [k]$ ,  $\gamma[k]$  are respectively the slope, lateral plate et and direction at  $k*T_2$  into the XYZ marks.

## 5. GPS measurement

Start : Latitude\_Degree1, Latitude\_Minute1

Longitude\_Degree1, Longitude\_Minute1

Arrival : Latitude\_Degree2, Latitude\_Minute2

Longitude\_Degree2, Longitude\_Minute2

Latitude1 = Latitude\_Degree1 + Latitude\_Minute1 \* 60;

Longitude1 = Longitude\_Degree1 + Longitude\_Minute1 \* 60

Latitude2 = Latitude\_Degree2 + Latitude\_Minute2 \* 60;

Longitude2 = Longitude\_Degree2 + Longitude\_Minute2 \* 60

### a. Distance to arrival

$$\delta\_Latitude = 1852 * |Latitude2 - Latitude1| * 60$$

$$\delta\_Longitude = 1852 * |Longitude2 - Longitude1| * 60$$

According with Pythagore:

$$Distance = \sqrt{\delta\_Latitude^2 + \delta\_Longitude^2}$$

**b. Course**

$\gamma$  is the course.

Scalar product:

North\_Longitude = 0

$$\cos(\gamma) = \frac{|\text{Latitude2} - \text{Latitude1}| * \text{North\_Latitude}}{\text{Distance} * \text{North\_Vector\_Distance}}$$

$$\gamma = \cos^{-1}\left(\frac{|\text{Latitude2} - \text{Latitude1}| * \text{North\_Latitude}}{\text{Distance} * \text{North\_Vector\_Distance}} * \frac{180}{\pi}\right)$$

Limited development of arcosinus:

PIC do not implement  $\cos^{-1}$  function, so a limited development replace this function:

$$\gamma \approx 3,1415927 - \cos(\gamma) - \frac{\cos(\gamma)^3}{3} * \frac{1}{2} - \frac{\cos(\gamma)^5}{5} * \frac{(1*3)}{(2*4)}$$

$$\text{with } \cos(\gamma) = \frac{|\text{Latitude2} - \text{Latitude1}| * \text{North\_Latitude}}{\text{Distance} * \text{North\_Vector\_Distance}}$$

**6. Distance to theoretical path (Y)**

Y is the distance to the theoretical path.

Management of going off the trajectory:

Fins corrects the course if  $|Y| > e\_max$ . So the SeaDiver Glider moves in a channel (between 2 values). An undershoot or overshoot curve will be performed if required.

Short duration corrections help to save battery power.

All of the corrections will be done when the SeaDiver Glider speed is at its maximum. So, SeaDiver Glider needs to anticipate correction.

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## **IX. POSITION MANAGEMENT SUB SYSTEM**

The underwater positioning is able to calculate:

**A. 2 GYROS:**

Pitch ( $\theta$ )

Yaw ( $\psi$ )

**B. 2 AXIS ACCELEROMETERS:**

Surge (X)

Heave (Z)

**C. GPS:**

-reinitialized surge and heave value.

-calculate turn angle value.

Fortunately, a system already exists and is inexpensive to buy. This board comes with the ET301 module, IMU 401/203, and ADXRS401 gyros already soldered as shown in the picture.

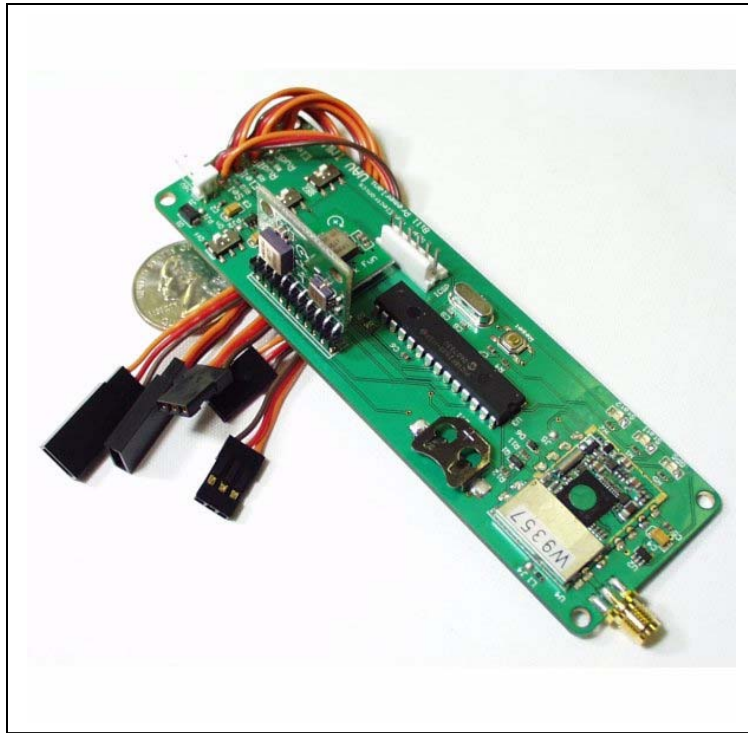


Figure 15. Position Management Subsystem

## X. AIR BALLAST DEVICE

Ballast must have the following characteristics:

- 150 PSI resistance for the bladder with a 1 gallon volume of air.
- Linear ballast inflation.

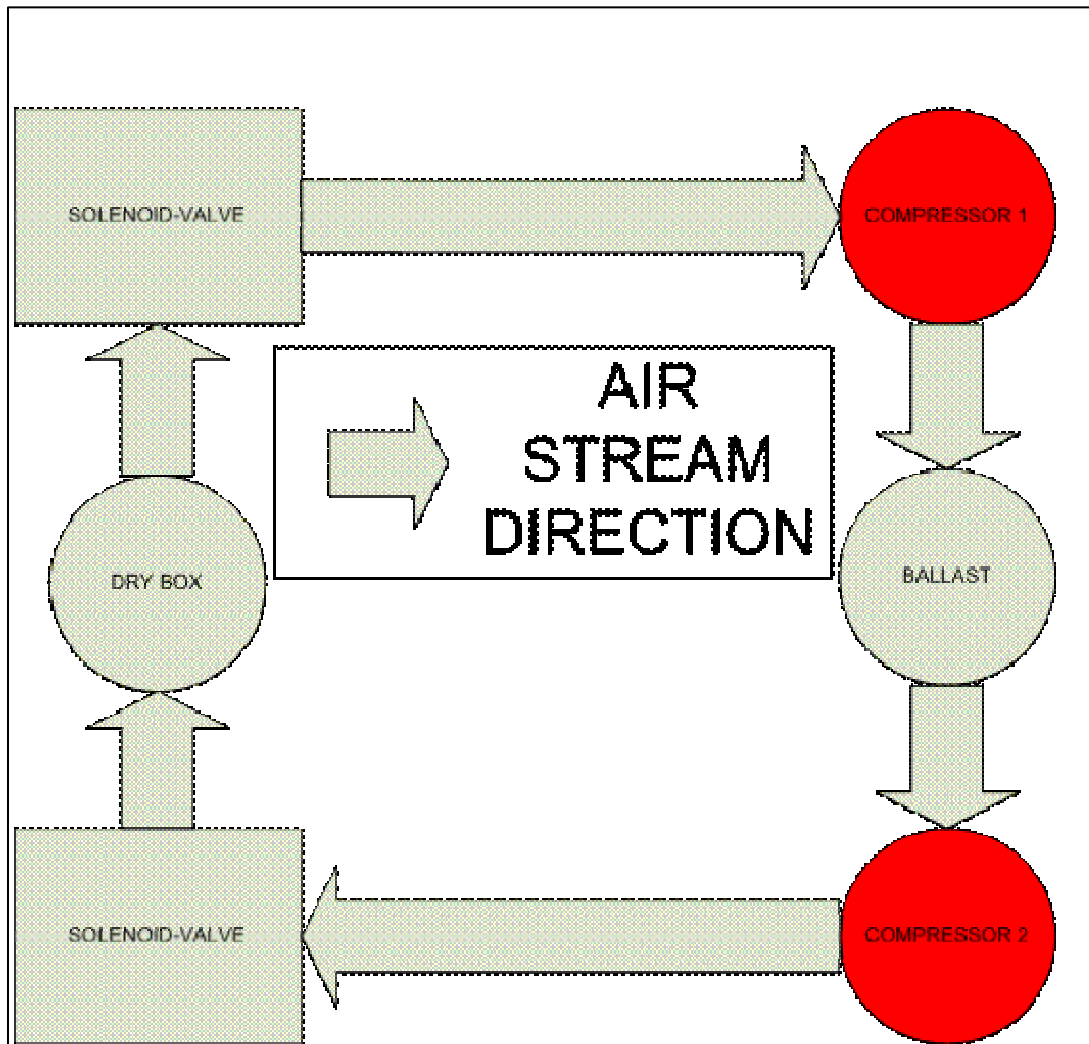


Figure 16. Diagram of the ballast cycle.

The use of an expansion tank for plumbing is a good match for the system requirements, as shown in the following figures.

## Product Features

*Deep Drawn Steel Domes for maximum strength & pressure rating*

*Rigid Poly-Propylene Liner for Corrosion Resistant Reservoir*

*Butyl diaphragm for long life expectancy. Tested to over 250,000 cycles*

*Diaphragm Hoop Ring mechanically grooved for permanent air-tight seal*

*Welded Steel Construction*

*Welded Air Charge Fitting with Protective Plastic Cap for Corrosion Resistance and Maximum Air-Tight Seal*

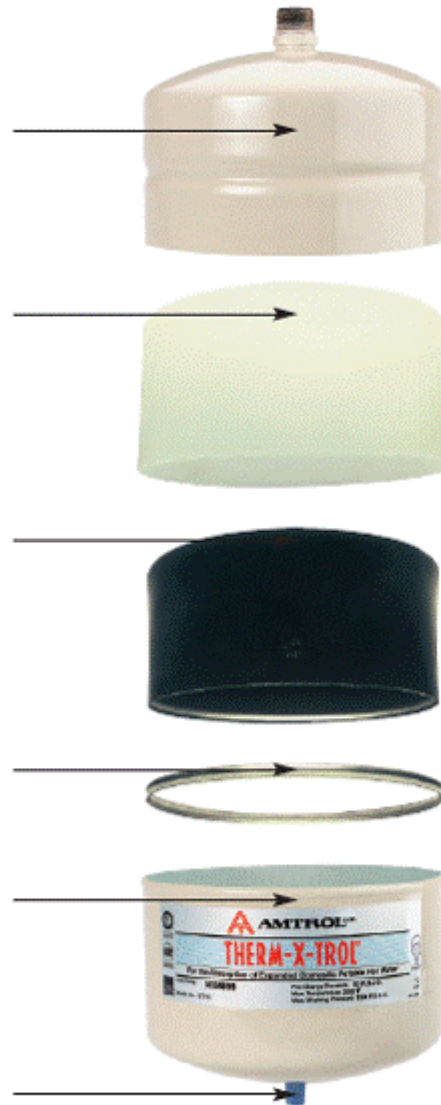


Figure 17. Ballast device features

Plumbers use such expansion tanks to allow water expansion when water temperatures vary.

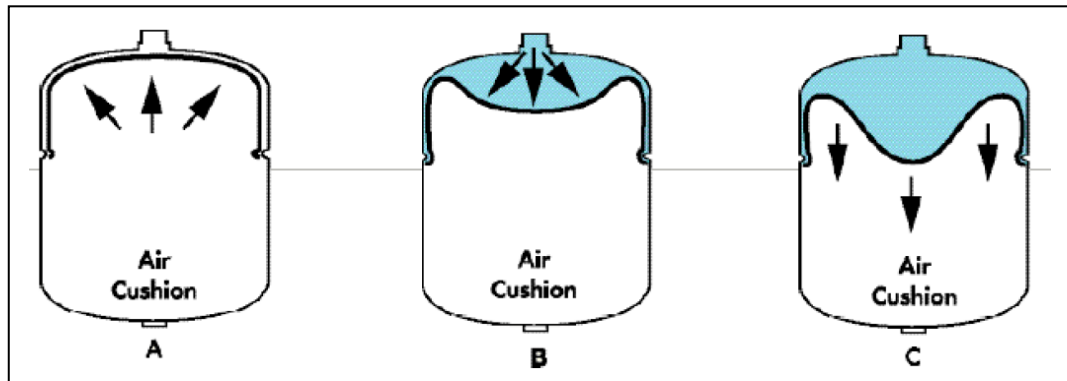


Figure 18. Water expansion

**A -**  
When the system is first filled with cold water, the expansion tank pre-charge pressure, which is equal to the fill pressure, keeps the diaphragm flush against the tank.

**B-**  
As the system water temperature increases, the expanded water is absorbed by the expansion tank.

**C-**  
As the system water temperature reaches its maximum, the expansion tank diaphragm flexes against the air cushion to allow for the increased water expansion.

Table 2. Table of Water Expansion in each Stage of the Ballast Device

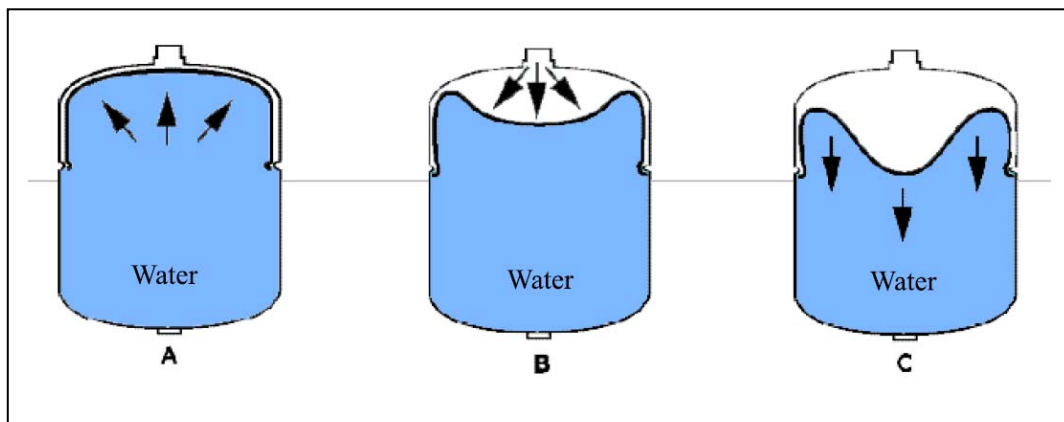


Figure 19. SeaDiver Glider's ballast.

<b>A-</b>	<b>B-</b>	<b>C-</b>
Expansion tank is full of water (without air), ballast is deflated → <b>SeaDiver Glider dives.</b>	SeaDiver Glider switch from a diving cycle to a rising cycle, ballast is filled up of air. Buoyancy changes linearly and the SeaDiver Glider changes his motion.	The expansion tank contains 0.9 gallon of air (maximum accepted volume)→ <b>SeaDiver Glider goes up</b>

Table 3. Table of Ballast Stages

## **XI. FUTURE WORK: VARIABLE BUOYANCY DEVICE**

A different device might be used to control the buoyancy with the collaboration of a French company Hydro Leduc oil pump. This device uses a displacement of oil instead of water. The air contained in a rigid box will be extended with the oil displacement. The constant area of the flexible tank allows accurate measurement of oil transferred volume, hence vehicle displacement, by using two linear potentiometers.

Standard low-viscosity hydraulic oil is fed into a boost pump before being sent to the high-pressure hydraulic axial piston pump. The addition of a separate boost pump provides the needed supply pressure to the high-pressure pump.

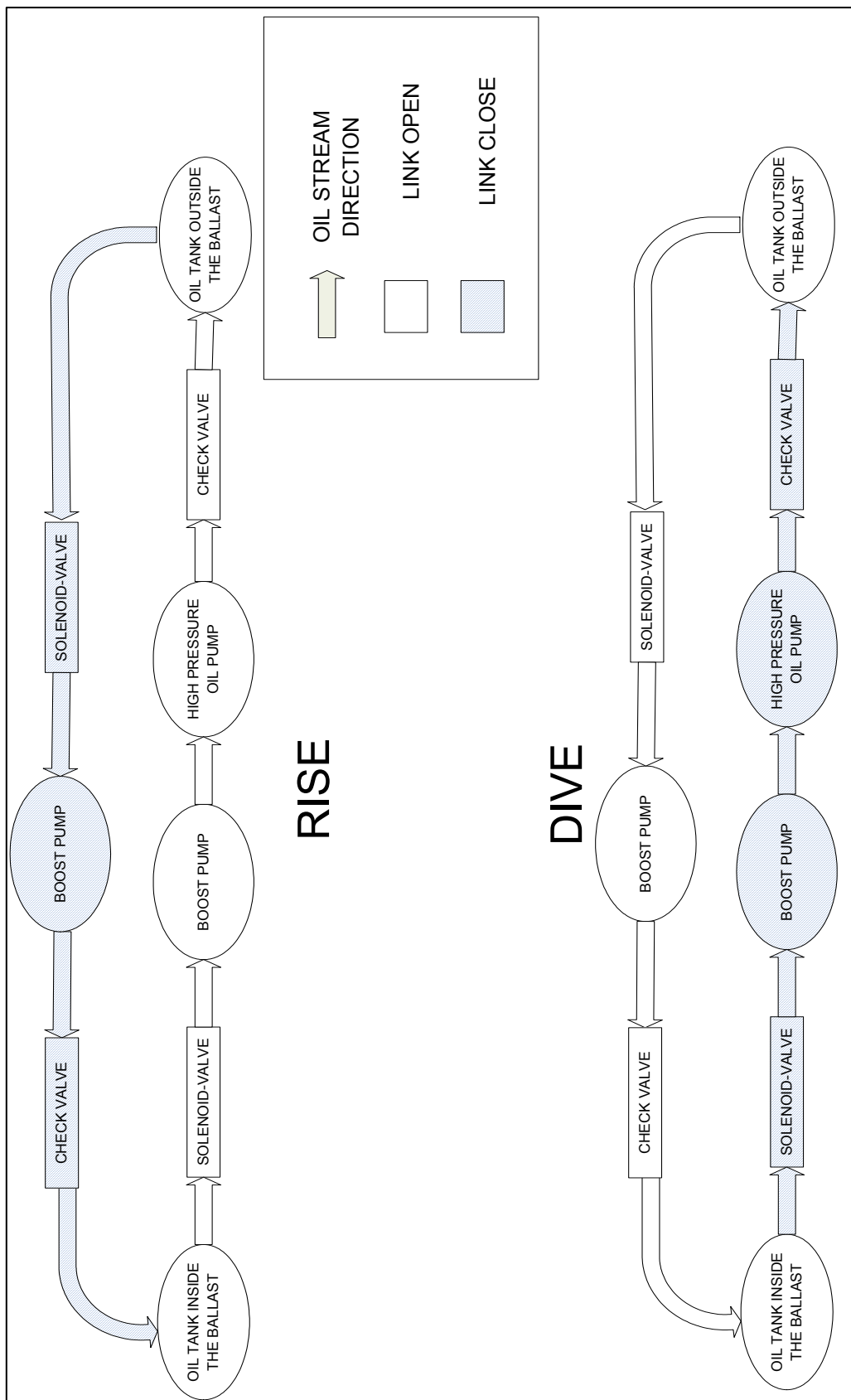


Figure 20. Variable Buoyancy device cycles



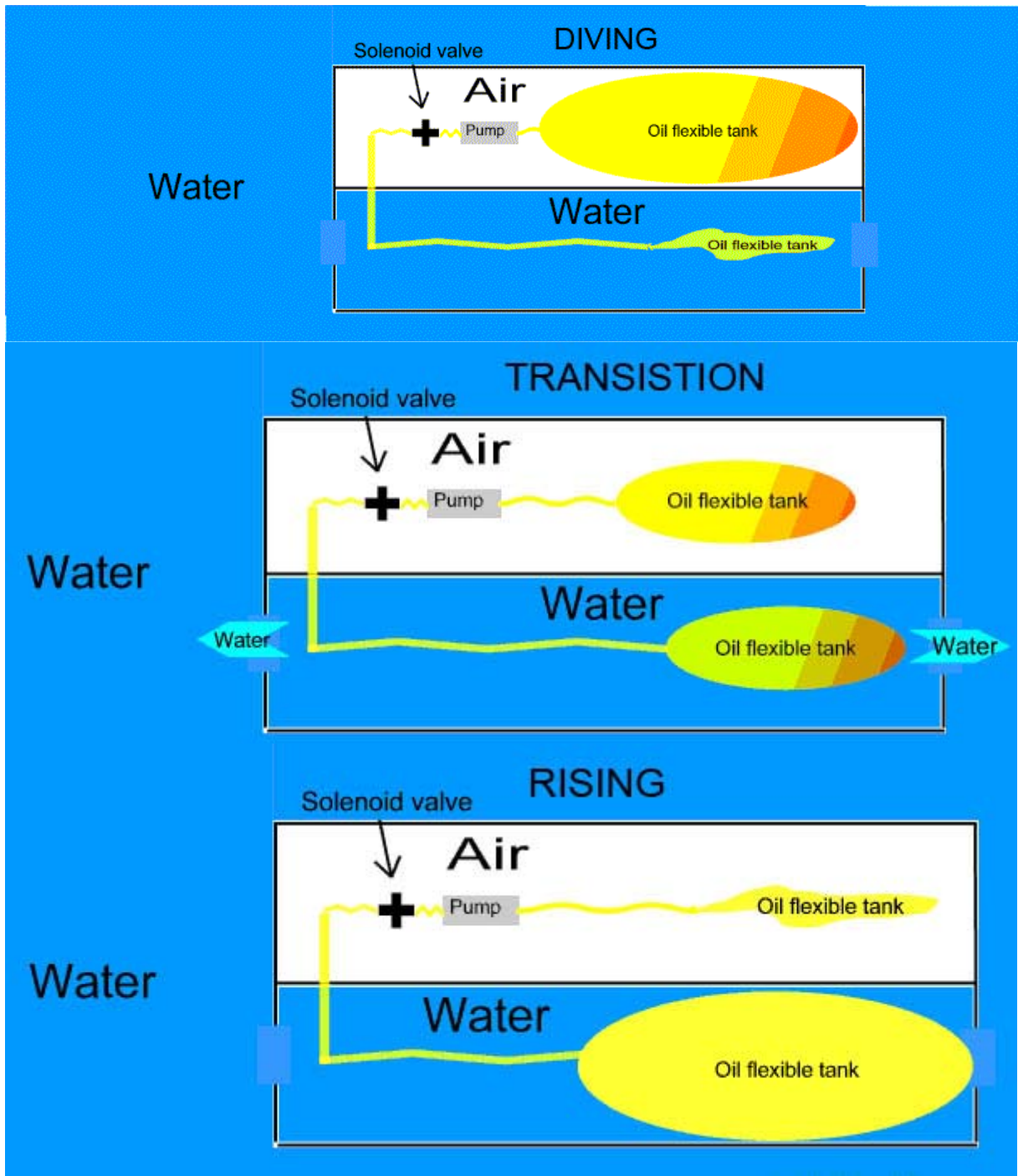


Figure 21. Diagram of Different States of the Variable Buoyancy Ballast cycles.

Volume occupied by the Variable Buoyancy Device is the volume of the dry box and variable volume of ballast. The system might use the same expansion tank for ballast, but the vehicle dry box will need to be bigger to get enough room for an oil tank.

SeaDiver Glider has the same weight but not the same volume. So it is more buoyant than at the first step using the Archimedes theory.

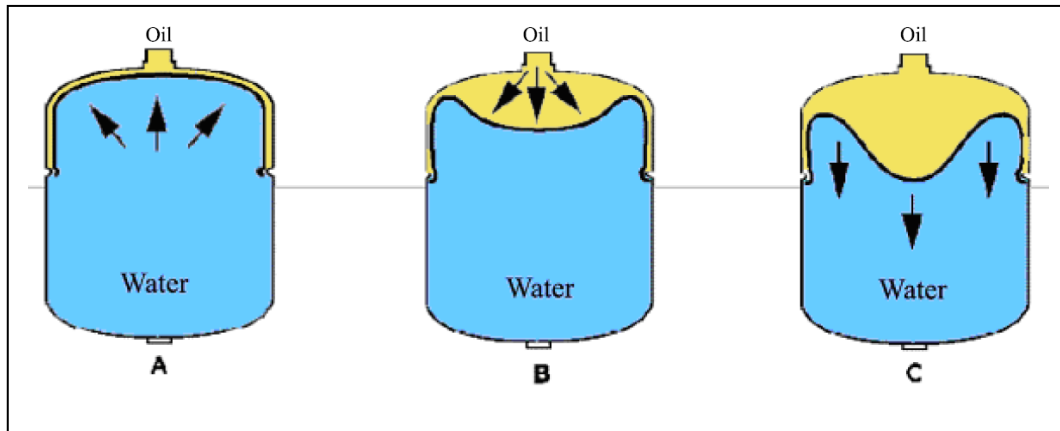


Figure 22. Ballast cycle.

Oil use instead of air use can enable more reliable volume management of ballast. The extreme limit of differential pressure obtained with oil pump is 10 times bigger than with air pump with the same energy consumption.

## **XII. POWER MANAGEMENT**

The SeaDiver Glider embeds one **Absorbed Glass Mat** (AGM) battery for air compressors, solenoid valves and servos. The GPS and wireless sensors platform is powered by 2 NiMH batteries (Nickel Metal Hydride)

AGM's cost 2 to 3 times as much as flooded batteries of the same capacity. In a long-running autonomous vehicle, fumes or leakage are an important concern. A standard or industrial deep cycle is not a good choice. AGM batteries main advantages are no maintenance, completely sealed against fumes, hydrogen production, or leakage, non-spilling even if they are broken, and can survive most freezes.

- Characteristic voltage: 12 V
- Capacity: 40 AH

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### **XIII. SIMULATION TOOLS: AUV WORKBENCH BY THE MOVES INSTITUTE**

The Naval Postgraduate School's (NPS) Modeling, Virtual Environments and Simulation (MOVES) Institute have developed an Autonomous Unmanned Vehicle (AUV) Workbench to simulate and test all types of autonomous vehicles as air-vehicles, ground, surface or submarines.

The AUV Workbench is developed in Java, and it is open source software, OS independent and available for free over Internet.

Insertion of autonomous vehicle dynamic and control characteristics permit a simulation of the vehicle behavior before have it built. AUV Workbench testing can show weakness and success. With this tool we hope to avoid the basic errors of mission's programming and to see if there are situations in which SeaDiver Glider might escape stable control.

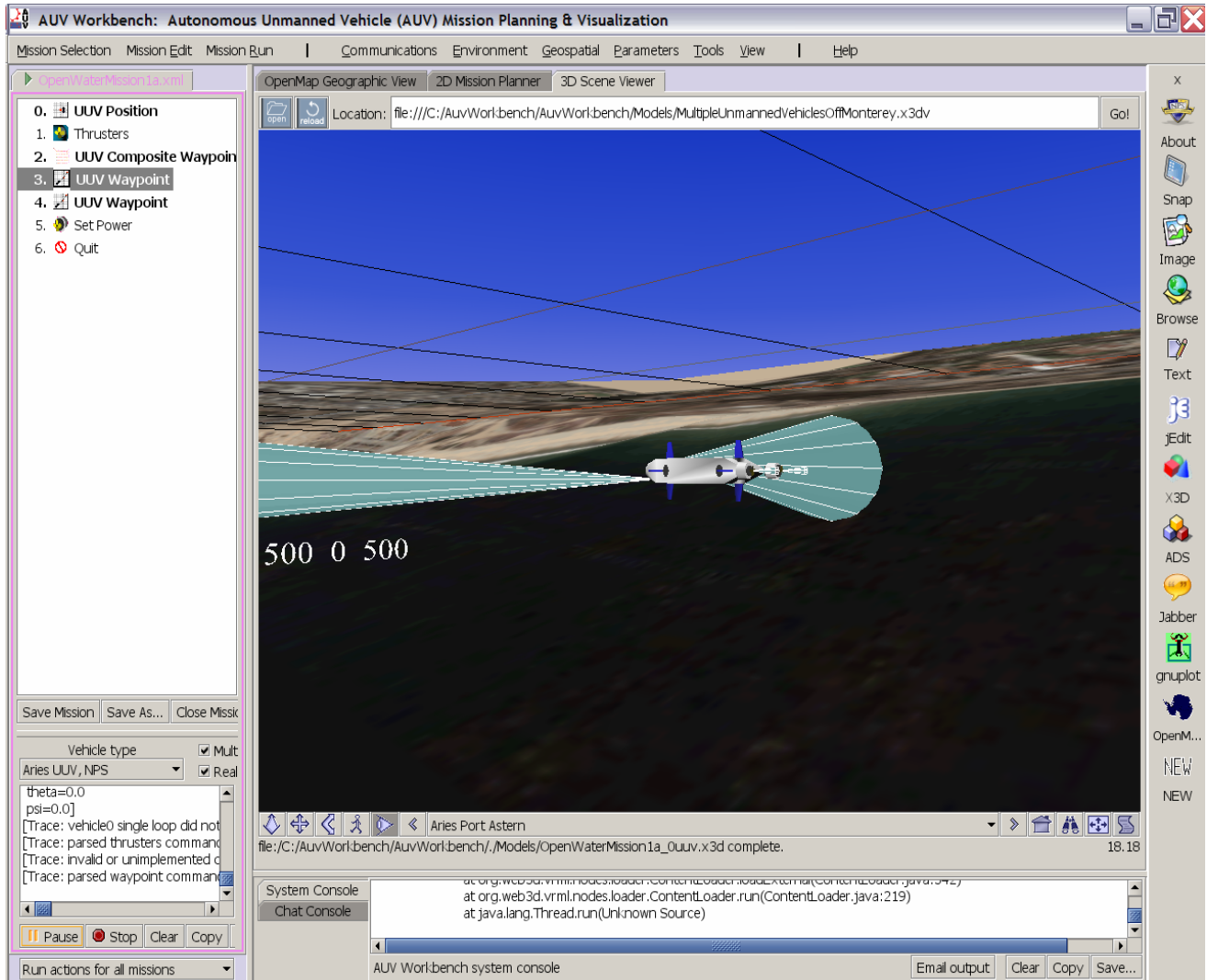


Figure 23. Screenshot of Multi-panels in the AUV Workbench

The software already includes various models of autonomous vehicles: Air, Underwater and Surface Vehicles (UAV, UUV and USV) and specific missions: cover and explore area, find a target, follow of an itinerary. The implementation of the SeaDiver Glider dynamics and control model inside the AUV Workbench had to be set up.

The existent model of the ARIES UUV has been taken to help the integration of the SeaDiver Glider.

Our work is to recover a model of underwater vehicle already present with close size and characteristics to the SeaDiver Glider and to modify them in the code to obtain the SeaDiver Glider's model.

**A. DIFFERENCES WITH THE MODELS ALREADY DONE**

- All thrusters' coefficients have to be zero effect.
- Add of a variable buoyancy term as ballast working directly on the dynamic equations
- Modify the Surge, Sway and Heave **Force** coefficients
- Modify the Roll, Pitch and Yaw **Moment** coefficients.

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## **XIV. CONSTRUCTION DIARY**

During the project we have learned a lot about how to conduct a project:

- **Estimating timing in a project: 90% of time to do 90% of the work and another 90% of time to do the remaining 10% of the end of the work.**
- Phone calls are always better than emails or research. We have made more progress with 20 minutes phone call than with 2 weeks emailing or researching.
- A local supplier may be 50% more expensive than an online supplier.

Very important questions used on a daily basis:

- What should I do now to progress with my project?
- Who is the person who could help me?
- International I need to link companies if they are not really efficient for that (bank → supplier, supplier → bank, supplier → supplier).
- Keep in contact with companies with a professional behavior. ☺
- 1st Law of engineering: if it works, don't fix it.
- In theory, theory and practice are the same, but in practice, they are different.

### **A. DATES**

05/13

- At the beginning, we had some troubles about the conception of the layout. Now, there is a CAD model of the layout (made with CATIA CAD Software from Dassault Systems).
- Choose and find all the components for the SeaDiver Glider:
- **Specifications were “low cost” and efficient**

06/24 ARIES UUV test day:

- A lot of idea from ARIES UUV project from the Naval Postgraduate School:
- Need radio communication between the boat and the SeaDiver Glider with power level and GPS monitoring to know where exactly the SeaDiver Glider is after the end of a mission.
- Add hooks in front of the SeaDiver Glider to troll it and so to calibrate it.
- Use of Digital instead of Analogical servos to have feedback of the planes position.

07/15

- Position of the ballast revised. The ballast is closer of the gravity centre.

07/19

- SeaDiver Glider added to the AUV Workbench:
- A buoyancy variable model added to the existing dynamics UUV model using the old surface wave model
- Identification of the source code and localization where dynamics terms need to be added to manage the buoyancy
- Control ballast added to the UUV model for using glider UUV like SLOCUM, ROGUE.

07/24

- Work with Don Brutzman and Duane Davis to add glider buoyancy model to the AUV Workbench.

07/25

- “L-3” conference meeting: add a new UAV to the workbench and for future work, add a moving avoidance obstacle system to the AUV Workbench.

07/27

- Duane Davis presentation: AV interoperability, Vehicle independent, XSLT Translation, Research of the fastest way to avoid obstacle, Research of the fastest path to cover an area (best is: TSP simulated Annealing coverage-pattern but not if you have a predetermined way), Add more autonomy intelligence to the AUV, because , at the beginning, there was just a waypoint following mode.

07/28

- We have ordered the material for the SeaDiver Glider hull; we will begin to build it next week.

07/31

- Meeting with Duane:
- Linear augmentation of the CB and implementation of a function to change progressively CB coordinates and buoyancy value.
- Focus on the dynamics coefficients, Page 47 to 52 of Don Dissertation: future work. Play with the coefficient.

08/05

- Material is arrived at the Monterey Bay Boatworks. Print of the SeaDiver Glider template.
- Improvement of the glider model in the workbench.

08/07

- Construction of the SeaDiver Glider: 2 days

08/09

- Open House at the MOVES Institute presentation of the SeaDiver Glider and the AUV Workbench to the public.
- Interview with a journalist.

08/11

- Draft of the dry box

08/14

- Beginning of the purchase request for the SeaDiver Glider future material

08/15

- Ballast, fins, dry box, and UUV platform are found.

## XV. CONCLUSION

This project has very great potential and must proceed through the first draft, especially for testing and giving results. All the subsystems can be tested apart before we link them together. This SeaDiver Glider will be totally autonomous with its **docking box**, which allows the SeaDiver Glider recharge its batteries and set up new parameters for another mission. This project is an open space to others in order to build a fully automated system which can cover a span of ocean for a month and transmit mission results.

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## **ANNEXES SUMMARY**

L-3 Meeting Report

An introduction to the AUV Workbench

Characteristics of different batteries

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## **AN INTRODUCTION TO THE AUV WORKBENCH** (*SOURCE: AUV WORKBENCH HELP TOPICS*)

1. The NPS AUV Workbench supports physics-based AUV modeling and visualization of vehicle behavior and sensors in all mission phases.
  - Animation based on vehicle-specific hydrodynamics that can be configured to model arbitrary vehicles by modification of the Java source code.
  - Models defined in X3D and VRML relying on Distributed Interactive Simulation Protocol allow visualization across networks utilizing custom software or off-the-shelf web browsers.
  - Virtual environment facilitates control algorithm development, control constant testing, mission generation and rehearsal, and replay of completed missions in a benign laboratory environment.
2. Graphical mission generation and data handling provides:
  - Automated generation of mission specifications using the XML-based Autonomous Vehicle Command Language (AVCL). This approach supports mission scripting, vehicle-to-vehicle, vehicle-to-agent, & vehicle-to-human communications, as well as storage of run-time telemetry data.
  - Automated conversion of AVCL mission into various arbitrary text-based AUV command languages using XSLT transformation.
  - Efficient serialization and transmission of generated imagery, telemetry and reports using XML Schema-based Binary Compression (XSBC) and Forward Error Correction (FEC) encodings.
  - Integrated sonar visualization capabilities.
3. XML-based Tactical Chat (XTC) provides open-source communications protocol among remote vehicles and individual operators, either in the virtual or real worlds.
  - Reliable asynchronous data transfer between AUV's, other vehicles, agents and human controllers.

- Automatic logging of all communications in a schema-constrained XML format that facilitates data retrieval for post-mission-analysis and mission reconstruction.

The X3D ISO standard defines a royalty free runtime system and delivery mechanism for real time 3D content and applications running on a network.

It supports several file format encodings and programming languages, providing unsurpassed interoperability for 3D data and significant flexibility in manipulating, communicating and displaying scenes interactively.

X3D incorporates the latest advances in graphics hardware, compression and data security to provide the best performance and visual impact in an extensible architecture that supports ongoing evolution.

X3D's XML-encoded scene graph enables 3D to be incorporated into web services architectures and distributed environments, facilitating the movement of 3D data between applications.

## L-3 MEETING REPORT

07/25:

<b>Long-term goals:</b>	How to incorporate the L3 algorithm to the workbench? How to add building in the x3d scene?
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Discuss L - 3 algorithm characteristics:

- Moving Obstacle avoidance system
- Non-Moving Obstacle avoidance system
- Searching for a target and neutralization of it.
- Real Time Area Definition for multiple UAV.
- Docking system after the neutralization of the target.
- Communication between each UAV. They know in real time where each one is.

L-3 practice tasks:

Agenda in the AUV Workbench:

- An agenda produce waypoint instead of a mission which waypoints are pre-calculated.
- Be able to modify default parameters of mission and run it

List of the bugs encountered: Romain will enter in issue tracker

- Add an Introduction to DIS protocol (link protocol between 2D planner and the x3D Scene) in the Help Topics or in the documentation (bug 1070).
- Add “New Agenda” line in the “Mission Selection” → “New Mission” menu (bug 1071).
- Zoom to fit current mission automatically when you open an agenda or a mission (bug 1073).
- In an agenda, geometry shape needs to display ID (bug 1075).
- XY label in the 2D planner with y = North and X = East, needs reorientation. (bug 1074).
- In the “Agenda Goal” pop-up, have to change “+” and “-“ to “Add” and “Delete” in each tab. (bug 1072).
- Impossible to re-size the mission tab. (bug 1069).

Next session: 08/01

- Duane will be there to look at the source code with L3 and hopefully where they could add their algorithm in the AUV Workbench.
- Draft agenda with Duane repeating the UCF demo, for single UAV

Following week:

- Add a new Unmanned Air Vehicle

Future sessions:

- Implementation of a new controller: virtual radar with the sonar model.
- Add the obstacle avoidance system for UAV.

## **CHARACTERISTICS OF DIFFERENT BATTERIES**

Selecting a battery need a lot of consideration:

Starting: 3-12 months

Marine: 1-6 years

Golf cart: 2-6 years

AGM deep cycle: 4-7 years

Gelled deep cycle: 2-5 years

Deep cycle (L-16 type etc): 4-8 years

Rolls-Surrette premium deep cycle: 7-15 years

Industrial deep cycle (Crown and Rolls 4KS series): 10-20+ years

Telephone (float): 1-20 years. These are usually special purpose "float service," but often appear on the surplus market as "deep cycle." They can vary considerably, depending on age, usage, care, and type.

NiFe (alkaline): 3-25 years

NiCad: 1-20 years

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