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Concept Design Of Autonomus Underwater Glider

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Abstract:

Underwater gliders are Autonomous Underwater Vehicles propelled by buoyancy change to follow a "Saw-tooth" pattern of motion in sea. They are characterised by long endurance, low speed and low cost. Unlike propeller-driven AUVs, Underwater Gliders use buoyancy for altitude change and wings to produce forward motion. They find applications in areas like underwater surveillance and oceanographic research/survey. Various technologies/methods are presently in use to produce the buoyancy change, which is the primary means of propulsion. This paper aims to review existing gliders and methods of buoyancy control in use, like piston driven buoyancy tanks, hydraulic fluid operated expandable bladders, methods under research like chemical propulsion etc. This paper also enumerates the methods adopted in designing a 1000 m diving underwater glider. The glider, designed in a modular concept where in the buoyancy engine, roll-pitch motion engine and sensors package are divided into modules which can be changed for repair / up gradation purpose.

1.Introduction

Autonomous underwater gliders are a type of Autonomous Underwater vehicles that do not use conventional propeller for propulsion..These vehicles glide through the ocean at low speeds using changes in buoyancy for vertical motion andwith wings itconverts vertical motion to inclined motion (Both vertical and horizontal).Gliders have longer deployment capabilities than standard powered autonomous underwater vehicles thus making them extremely valuable for long term oceanographic research/survey.

2.Application

Oceanographic data is generally collected by remote sensing, ships fitted with instruments, autonomous underwater vehicles etc. The above methods are limited by their range and cost of operation. Independent operation, low cost with long endurance qualifies under water gliders as superior alternative for oceanographic data collection.They gather oceanographic data like conductivity and temperature continuously and transmit it to the base.

Variant of these gliders also find applications in military like surveillance, intelligence gathering etc. Gliders have little impact to the environment and provide minimum threat to sea creatures.

3.Operation

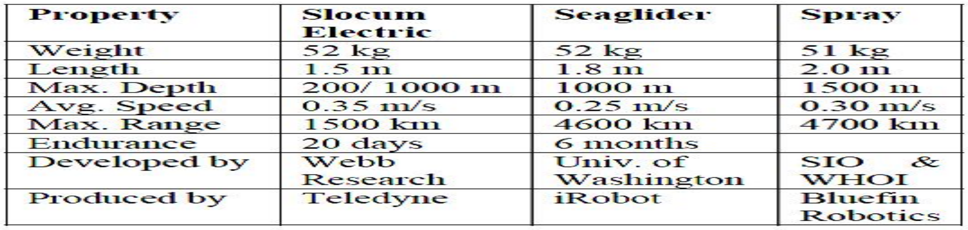
Gliders are deployed for long duration with the onboard stored battery power. The energy required for propulsion is for charging buoyancy of the glider. Buoyancy is changed by varying thevehicle volume. Wing lift and body drag are balanced by the net buoyant force in steady glide. Change in volume occurs at the top and bottom of each glide cycle.

At the end of each cycle, glider surfaces and establishes communication with a satellite. The data collected in each glide is transmitted to the base station via this link. Instructions set including change in the path and other data are transmitted to the glider which is then implemented by an onboard computer.

Controlling the hotel load and sensor load helps the glider in maintain its long endurance and high range. Since drag is roughly quadratic, halvingspeed roughly increases range by four.The characteristic that clearly distinguishesgliders from other AUVs is not theirmeans of propulsion but rather the fact thattheir very slow speed and consequent lowdrag permit long-duration operations. The main factors influencing rangeper unit energy consumption are operatingspeed (fast is inefficient), depth (shallowoperation is inefficient), vehicle hydrodynamicdrag, and the combination of oceanstratification and the difference of compressibilitybetween the glider hull and seawater.

4.Existing Gliders

Three widely used gliders in today's world for commercial operations are products of the Autonomous Ocean Sampling Network program of the Office of Naval Research (ONR), US Navy. These are often called as 'legacy' gliders and their main characteristics are summarized in Table 1. The Slocum Electric Glider (Figure 2) developed by Teledyne Webb Research ; the Seaglider (Figure 3), developed by the University of Washington ; and the Spray (Figure 4), developed by Scripps Institute of Oceanography (SIO) and Woods Hole Oceanographic Institution(WHOI). Nearly 160 commercially available gliders of these three types were in operation in 2009.



Property	Slocum Electric	Seaglider	Spray
Weight	52 kg	52 kg	51 kg
Length	1.5 m	1.8 m	2.0 m
Max. Depth	200/ 1000 m	1000 m	1500 m
Avg. Speed	0.35 m/s	0.25 m/s	0.30 m/s
Max. Range	1500 km	4600 km	4700 km
Endurance	20 days	6 months	
Developed by	Webb Research	Univ. of Washington	SIO & WHOI
Produced by	Teledyne	iRobot	Bluefin Robotics

Table 1: Characteristics of Legacy Gliders [1]

5.Design Aspects

5.1.Preliminary Design

The staff targets for design are shown in Table 2. The initial steps in design of a glider areselecting the mission requirements, sizing the main components, and choosing the body geometry. Mission requirements include range, endurance, speed and payload. These will determine the glider's power requirements. Glider internal volume is a specific design limit as it can determine the space available for batteries, payload and other components. Based on the results published in [6], it can be concluded that the increased size of glider leads to higher speed and lower endurance (high power requirement).

Role Profile	(a) Intelligence Surveillance Reconnaissance (ISR)(b) Harbor Patrolling(c) Military Oceanography
Displacement	50 Kg (approx.)
Speed	(a)Vertical: 0.1 m/s(b)Horizontal: 0.3 m/s
Range	1500 km (approx)
Endurance	20 days
Depth of Operation	1000 m

Table 2: Staff targets for Design

The Autonomous Underwater glider design is based on the legacy gliders design. The initial applications considered are collection of hydrographical data namely conductivity, temperature and depth. In addition the glider, envisaged for a military role, its mission included collection of video or still photographs. The data collected is to be stored and then transmitted to the base via a communications satellite. The mission profile thus encompasses the basic oceanographic data collection process and takes a step towards military application by including Intelligence gathering, Surveillance and Reconnaissance (ISR) in the objectives.

Based on the mission profile the following sensors (payload) are selected.

- Camera
- Obstacle avoidance sonar
- CTD

Existing glider designs were evaluated and based on them the arrangement of sensors was done. Preliminary estimation gave rise to dimensions Length 1.8 m and Diameter of 0.2 m.

5.2.Glide Path

Glide path of a glider can be divided into transient phase and steady glide phase [12]. In transient phase, the glider experiences continuous change of weight/buoyancy due to action of the buoyancy engine. Due to imbalance of forces, accelerations are present in this phase. In steady glide phase, a force balance exists, leading to a uniform velocity glide. All gliders tend to move in steady glide phase for maximum duration of glide and cover large distances. Design is done for steady glide.

The angle for steady glide was fixed as 35 degrees [6]. Increase in buoyancy to maintain that angle was estimated as 160 g of water.

To maintain a positive attitude when at surface, glider is designed to have 140 g of positive buoyancy. 160 g of buoyancy is given to maintain the required glide angle in steady glide. Thus the capacity of buoyancy engine was fixed as 300 g.\

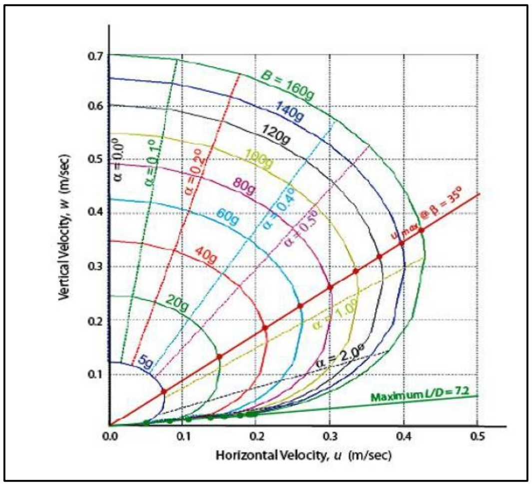


Figure 1: Glide polar (spider plot) of legacy glider. Polar contours appear as concentric solid curves for loaded mass B = 5 to 160 g. Dashed radial lines are contours of constant angle of attack, α. [1]

5.3.Buoyancy Engine

The existing literature gave rise to three options for a variable buoyancy engine [13], [14].

- Piston operated tanks
- Hydraulic pump with external bladder
- Chemical Propulsion

Buoyancy engine with piston operated tanks has been selected due to simplicity of operation. A model of the same for demonstration purpose was made. Total buoyancy capacity is divided into six tanks of 50 g each. This is done to attempt an experimental study by isolating few tanks and study the effect of various values of negative buoyancy on the trajectory of the glider.

The pistons of the tanks are operated by a rack and pinion arrangement. This is driven by a DC motor. The power requirements vary with the speed of operation of the pistons.

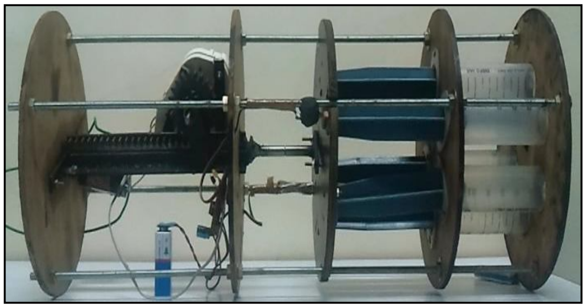


Figure 2: Demonstration model of the buoyancy engine with piston operated tanks.

5.4.Hull Form Selection

Options to explore for hull form are listed below.

- Myring hull form (Slocum)
- Blended wing (Liberdade class)
- Aerofoil shape body

Hull form decides the drag characteristics of the glider and also the internal volume available for the components. Sticking to the legacy glider convention, a Myring hull form was selected. The overall length of glider is 2.3 m with 1.8 m pressure hull that houses the systems, an aft tail cone and nose section. The latter two sectionsare freely floodable and house the camera, sonar and CTD.

5.5.Wing Design

Glider's wings convert vertical motion to horizontal motion. They can be fixed or movable. The fixed wings are designed such that when the glider attains steady glide, the angle of attack for wing is attained by the attitude of the glider. The principle behind the design procedure is same as that of the aeroplane wing design.

Based on [7] and [15], a procedure was developed for calculating the drag and lift coefficient of the glider (including body and wings). The value of lift and drag forces thus developed should balance the net buoyancy (difference of weight and buoyancy) acting on the glider.Iterations are done for a selected wing form (in this case taken from legacy gliders) to match lift, drag and forward speed.

The summary of procedure is listed below

- Fix the wing plan form and dimensions
- Select a velocity profile based on the glide path angle. Sweep angle can be selected as per iteration

- Parasite drag coefficients for body and wing are calculated. Induced drag for wing is estimated using the aspect ratio formula and for body, it is taken either from experimental data or parent ship.
- Angle of attack calculated by solving the implicit equation
- Lift and drag coefficients are calculated
- Lift and drag force calculated are checked with required Lift and Drag forces for satisfying the force equilibrium.

  The final dimensions of the wing and the velocity attained is shown in Table 2.

1.	**Angle of attack**	2.9°
2.	**Glide angle**	35 °
3.	**Sweep angle**	15 °
4.	**Wing Span**	0.5 m
5.	**Wing Chord**	0.2 m/0.07 m
6.	**Velocity**	0.4 m/s
7.	**Lift**	1.194 N
8.	**Drag**	0.837 N

Table 3: Design Wing Particulars

Antenna for communication with the satellite is embedded into one of the wings. Thus when the glider surfaces, it rolls to its side making the antenna clear of the water and the communication is established. The necessary moment for the roll is provided by a dedicated pitch and roll control.

5.6.Pitch And Roll Controller Design

The design of pitch and roll control is based on [8]. The principles are discussed below. Pitch and roll control of underwater gliders is normally provided by internal actuation. Internal actuation refers to the manipulation of the vehicle's center of buoyancy and/or center of gravity to control movement. The control system normally employed involves moving the glider's battery pack(s) to change the center of mass. By sliding the battery pack forward or aft the vehicle's center of mass moves horizontally, controlling pitch. By rotating the battery pack about the longitudinal axis of the vehicle, the center of mass can be shifted to one side. This causes the vehicle to roll, instigating a change in yaw. System will be used for roll and trim correction occurring due to:

- Sea currents
- Turning effects
- Communicating when on surface

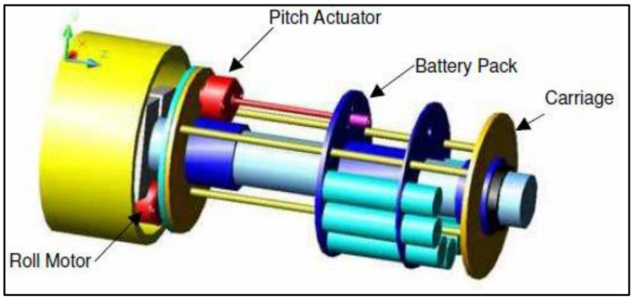


Figure 3: Pitch and Roll controller [8]

The design involves rotating the carriage, and sliding the battery pack inside this cage. The outer carriage is 20cm long and allows the battery pack 10 cm of travel. The carriage has an outside diameter of 3.75" and can rotate through 360. The carriage is rolled using a stepper motor attached to the shaft. There is a small spur gear attached to the motor, which meshes with a larger internal ring gear attached to the carriage.

Sizing the motor for roll control was more detailed. The critical parameter for this sizing was hold torque. The design value of hold torque was obtained by considering the worst-case scenario for roll. When the carriage is rolled to 90° left or right, the CG of the batteries is furthest offset from the centerline. In this case the moment created by the batteries is partially offset by the moment created by the pitch actuator mounted on the top half of the carriage

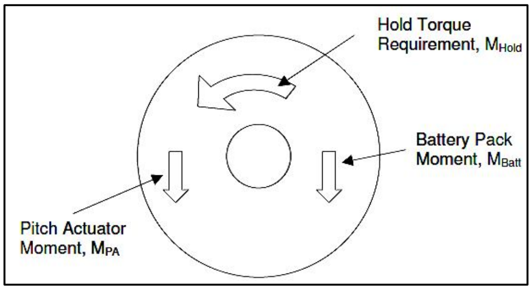


Figure 4: Free body diagram of carriage

5.7.Pressure Hull Design [9], [10]

There are four prime steps in designing a pressure hull for an underwater vehicle.

- Selection of the shape of the hull
- Material Selection
- Hull thickness requirement based on depth limit and safety factor
- End closures design compatible with the hull and design requirement

Based on recommendation of Ross C T F [16], the shape of the hull was selected as circular cylinder. A study done on the materials for underwater submersibles by James et al [17], resulted in selection of Aluminium 6061 T6. The properties of the material are given in Table 3.

The Length / Diameter ratio of the pressure hull of glider is 9. This value is in the range of long thin cylindrical shell. Structural strengthening of such a cylinder was studied by Faulkner D in [10]. The same procedure is done and two options were studied. One being a stiffened cylinder and other being unstiffened cylindrical shell.Finite element analysis of the same was carried using ABAQUS. The study is in progress.

Comparison of the structural design using Aluminium alloy was done with Hy 80 steel. Results are shown in Table 4.

Property	**Value**
Elastic Modulus	68900 MPa
Yield Strength	276 MPa
Poisson's Ratio	0.33

Table 4: Material Properties of Aluminium 6061 T 6 alloy

Name	**Thickness (mm)**	**Weight (kg)**
Al 6061 T 6	12	16.3
HY 80 Steel	11	47.3

Table 5: Comparision of Aluminium alloy design and HY 80 steel design

5.8 .Hydrodynamics And Simulation

The maneuvering and control of the underwater vehicle is very important since their attitude and velocities will determine the glider trajectory. This in turn will affect the endurance and path alteration capabilities of the glider. Several assumptions were made for the derivation of the dynamics model for the vehicle.

The first step was to obtain the hydrodynamic coefficients of the vehicle. A number of methods have been proposed for the determination of hydrodynamic coefficients. They can be broadly broken down into test-based and predictive methods. The former include direct experimental determination based on wind-tunnel or tow-tank model tests as well as testing of full-size captive vehicles. Predictive methods offer an alternative to test-based methods when the vehicle is still in the design stages, or when costs prohibit a full-scale testing. Predictive methods are most likely to yield reasonable results when applied to streamlined vehicles since the behavior of these is more easily predicted [1]. The 'Legacy' gliders fall into this category. Empirical means are the most widespread of the predictive methods. Here, the coefficients are calculated using the methods given by Timothy Prestero [11].The vehicle is decomposed into its basic elements, including hull, wings and fin, and the coefficients for each component is calculated.The forces and moments acting on the vehicle are then determined through a summation of the component effects, along with coefficients to account for the interference effects.

5.8.1.Vehicle Model

The dynamic model for our glider is based on SLOCUM [11], AUVs and airships [1].These works outline a component buildup approach to the dynamic modeling of vehicles which derive their lift via buoyancy, though they differ in the manner in which the equations of motion are formulated.

5.8.2.Equations Of Motion

In order to develop the equations of motion for the Glider, 2 reference frames are established. The first is a body-fixed frame whose origin is set at the center of buoyancy of the vehicle and oriented in the customary aeronautical manner, i.e. with the +x-axis pointing forward through the nose, the +y-axis outward through the starboard wing and the +z-axis pointing downwards. The second frame is the Newtonian (inertial) frame whose axes are oriented such that the +Z axis points downwards towards the ocean floor, i.e. in the direction of increasing depth. Using these frames, the vehicle's position in space is described by the position vector from the origin of the inertial frame to the origin of the body frame, and its orientation is given by the 3 Euler Angles, i.e. roll (φ), pitch (θ) and yaw (ψ).

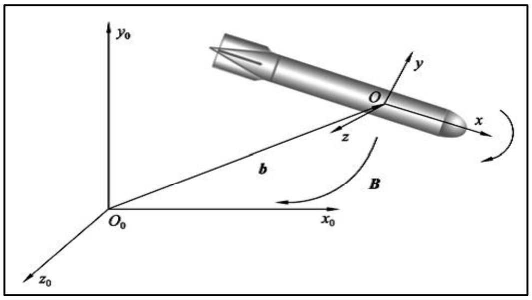


Figure 5: Frame of Reference for glider [5]

5.8.3.Summary Of Procedure

The steps needed to implement the above procedure can be summarized as follows:

- The initial conditions are selected u,v,w,p,q,r =0
- The accelerations u', v', w', p', q', r' are calculated as follows.
- The values obtained are integrated to yield the velocities(u,v,w,p,q,r) and displacements (x,y,z,φ,θ,ψ)at definite time steps. These are used as initial values for subsequent calculations. The procedure given above has been implemented in a MATLAB program to performing all calculations and integration of the differential equations of motion using Runge Kutta method.
- The calculation is continued till the acceleration values vanish i.e. Steady glide path u', v', w', p', q', r'=0.
- The velocities and displacements obtained at each step is recorded and plotted to define the glide trajectory.

6.Conclusion

A detailed concept design an Autonomous Underwater Glider with weight estimation has been designed and the procedure adopted is brought out in the paper. A prototype model of the glider is envisaged from the design study for further experimental analysis.

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m - Y_{\dot{v}} & 0 & -mz_g & 0 & mx_g - Y_{\dot{r}} \\ 0 & 0 & m - Z_{\dot{w}} & my_g & -mx_g - Z_{\dot{q}} & 0 \\ 0 & -mz_g & my_g & I_{xx} - K_{\dot{p}} & 0 & 0 \\ mz_g & 0 & -mx_g - M_{\dot{w}} & 0 & I_{yy} - M_{\dot{q}} & 0 \\ -my_g & mx_g - N_{\dot{v}} & 0 & 0 & 0 & I_{zz} - N_{\dot{r}} \end{bmatrix}^{-1} \begin{bmatrix} \sum X \\ \sum Y \\ \sum Z \\ \sum K \\ \sum M \\ \sum N \end{bmatrix}$$

Figure 6: Equation of Motion [6]

- **NOMENCLATURE**

u = Linear velocity of glider in x-axis

v= Linear velocity of glider in y-axis

w= Linear velocity of glider in z-axis

p= rotational velocity about x-axis

q= rotational velocity about y-axis

r= rotational velocity about z-axis

$\dot{u}$,$\dot{v}$, $\dot{w}$,$\dot{p}$,$\dot{q}$,$\dot{r}$=accelerations of the glider in above mentioned directions

X= Force acting on glider in direction along x-axis

Y= Force acting on glider in direction along y-axis

Z= Force acting on glider in direction along z-axis

K=Moment acting on glider about x-axis

M=Moment acting on glider about y-axis

N=Moment acting on glider about z-axis

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