DESIGN OF A MOBILE AND BOTTOM-RESTING AUTONOMOUS UNDERWATER GLIDING VEHICLE

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Abstract

Most AUVs, and particularly Autonomous Underwater Gliding Vehicles (AUGV), must remain in motion or maintain neutral buoyancy at controlled depths with little or no propulsion. The ability to be both mobile and bottom-resting creates many desirable features in a glider. A mobile to stationary conversion will allow a traditional, bottom mounted sensor platform to be deployed from over the horizon, covertly move into position, and then become a bottom fixture. A central problem is that even gliders, despite their ability to control buoyancy, typically have limited dynamic range of buoyancy and the downward force available is modest. This creates a risk that the glider will be pushed around by the bottom current. Although the present glider design of a cylindrical fuselage with wings and tail could be settled on the bottom, a more suitable design is proposed. A vehicle of lenticular or ellipsoidal shape, having low drag in the horizontal bottom current, can have a rugged exterior to resist abuse if it is pushed around.

In order for a bottom-resting vehicle to resist trawls and dredges, it must be capable of attaching itself to the bottom of the ocean. To this effect, an efficient method of anchoring to the bottom must be devised and tested. This paper will cover the design and implementation of a mobile, ellipsoidal glider with bottom-resting capabilities. Design issues include internal and external architecture, energy sources, buoyancy drive, anchoring and mooring techniques.

Introduction

The need for long endurance AUV sampling

Most AUV performance today, despite large advances in sensor technology, remains hindered by the vehicles' limited endurance and sampling time. To sample important events, they must be either well-forecasted for prompt AUV deployment or an AUV must have the endurance to continuously sample throughout a period of time that includes these events. An important evolution in the maturity of AUV technology is the capability of a vehicle to go into quiescent mode during periods of low activity and to become active if an important event occurs. This method both increases endurance and restricts sampling to only preprogrammed events of interest. Despite the multiple advantages this approach would provide, two major drawbacks are immediately apparent. Programming a vehicle to sample a definite set of events would require advanced detection and sampling algorithms that would minimize the possibility of missing relevant occurrences and skewing data. In addition, before going into quiescent mode, a vehicle must be capable of determining its position and status after waking up. This implies that the vehicle must remain in a fixed position during 'sleep' by attaching itself to the bottom or be capable of tracking its motion. Power and mission considerations suggest bottom resting as the most reasonable approach.

Bottom resting requires new design consideration

Given that traditional cylindrical-hull gliders have a limited dynamic range of buoyancy, the downward force available is modest and therefore settling on the bottom by using available buoyancy variation creates the risk that the glider will be pushed around by the bottom current. In addition, the cylindrical hull structure is not the most favorable form for bottom settling, making itself vulnerable to bottom currents due to its small bottom contact area and high aspect ratio (Figure 1). A more suitable design would be a vehicle of lenticular or ellipsoidal shape, having low drag in the horizontal current, and a rugged exterior to resist abuse if pushed around. This vehicle would present a larger bottom resting area and a lower horizontal aspect ratio.

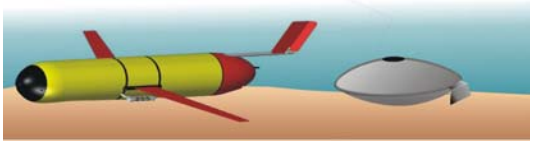

Figure 1 – Cylindrical glider vs. Lenticular glider resting on bottom sediment

Background on disc-shaped and bottom resting vehicles

The concept of bottom stationing for sensor deployment is not a novel idea and has been implemented in Florida Atlantic University's Ocean Explorer AUV. The Ocean Explorer system provides a large buoyancy variation capable of making the vehicle significantly negatively buoyant and thus keeps the system stable even in bottom currents. The sensor array is then deployed; the AUV goes into a 'quiet' mode where all motors, acoustic systems, etc are powered down while measurements are being made. Once measurements are completed, the array is retracted and the AUV regulates its buoyancy back to slightly positive and continues its mission.

For an underwater glider, the process is slightly more complicated due to the limited energy budget available. Settling on the bottom can be readily accomplished by becoming negatively buoyant. Glider missions are expected to span months as opposed to days and the challenge arises in maintaining this unique feature in addition to providing multiple liftoff events.

An additional constraint is the shape, optimized for robustness and trawl resistance. Concerning air vehicles of circular plan-form, history is diverse, starting with the development of a circular planform flying wing (XF-5U-1) during the 1930's and 40's [1]. In the 1950's, a Vertical Take Off and Landing (VTOL) air-vehicle known as the Avrocar was developed [2-4]. In the early 1960's, NASA investigated the suitability of disc shapes for re-entry vehicles [5-6]. In more recent times, after the boom of the technology age, it is not surprising that the disc-wing is re-emerging as a candidate for unmanned air-vehicles (UAV's). The Cypher VTOL UAV (Sikorsky Aircraft Corporation), the Cypher II Marine variant (Figure 2a), also known as 'Dragon Warrior', the SiMiCon Rotor Craft (Figure 2b) UAV [7-8] all have circular planform fuselages with various rotor blades and control surfaces. On a smaller scale was the mid-1990's six inch AeroVironment Micro Air Vehicle (MAV) and the redesigned Black Widow MAV of 2001 [9].

Figure 2a - Cypher II – Dragon Warrior, courtesy of Aurora Flight Sciences

Figure 2b - SiMiCon Rotor Craft (SRC), courtesy of SiMiCon AS

The applications and opportunities for the implementation of a discus shaped marine vehicle have not yet been investigated. Most realized ellipsoidal configurations in the ocean today are mines and stationary buoys.

Vehicle Design Goals

The principle objective of this vehicle is to function as a cost-effective and convenient platform for underwater surveillance of environmental, biological, physical and human elements in denied littoral zones. To accomplish this goal, the design parameters listed in Table 1 below have been defined.

Shape	Lenticular Discus	Optimal shape for both gliding and bottom resting
Size	Diameter: 30'', height: 10''	Ease of handling and deployment
Mass	40Kg	Ease of handling and deployment
Stability	Controlled Buoyancy, Dynamic Pitch/ Roll Control	Steering and Navigation
Propulsion	Rotary Displacement Pump	Used for both gliding and bottom resting
Power	Alkaline D-cell batteries	Low-cost, easy to transport
Payload	5 L payload volume with separate computing capability	Enough for most sensors, added computation capabilities
Depth	4m to 100m	Cover most littoral areas
Range	100-500 Km	Over the horizon deployment
Endurance	3-6 months	Station keeping and monitoring for entire duration of event

Table 1 – Discus Glider Design Parameters

Advantages of a both mobile and bottom-resting gliding vehicle are extended endurance, selective sampling, anti-submarine warfare applications, quiet operation, over the horizon deployment, small, hard-to-detect shape and relatively low-cost production. On the other hand, a number of disadvantages are immediately obvious, including limited power availability, limited sensor payload, limited number of ascents to surface, a slow advance rate and limited communication bandwidth. Many of these obstacles can be overcome by using a low-drain quiescent state, limiting payload sensors to the necessary, ascending only on defined triggers and transmission of location and abbreviated messages.

Vehicle Description

The vehicle is currently under construction and will be based on the design outline shown in Figure 3a and 3b**.** The following sections outline the architecture of the vehicle, cover the propulsion mechanism and navigation, describe the bottom resting and release mechanism, explain some of the control architecture and delineate some of the vehicle hydrodynamics from available aerodynamic data.

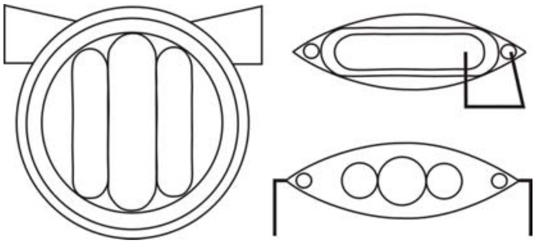

Figure 3a - Discus Glider 30'' diameter, 10'' high configuration

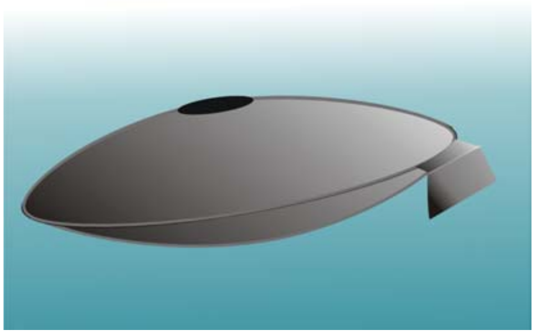

Figure 3b – Design concept of Discus Glider

Proposed Architecture

The volumetric advantage of a discus is quickly lost in water where cylindrical pressure housings within the ellipsoid are most likely required to withstand the water pressure. Additional consideration is required to determine the internal and external architecture of the glider. The design currently includes three carbon fiber pressure hulls with aluminum end caps fitted into the lenticular hull. The carbon fiber hulls, built for maximum pressure under compressive loading, have a flexural modulus close to that of a common aluminum alloy used in many pressure vessels today and will thus provide the same pressure resistance. Hulls using low-density carbon fiber composites weigh less than the conventional aluminum hulls. The center hull, being the largest of the three, will carry electronics and the buoyancy engine. The smaller hulls on each side will carry the power sources, making them readily replaceable, and providing flight stability to the vehicle by having the weight equally distributed inside the vehicle. A torroidal ring, circumscribed around the pressure vessels, will contain the buoyancy-drive volume.

The external shell will be made of a variable-density, syntactic foam molded to fit the internal components. Surface finishes and protective coatings offer high level impact and abrasion resistance and are quite durable.

To determine the hull sizes required, a preliminary outline of the glider contents and power budget was drafted, which helped to define volumetric and buoyancy requirements for the vehicle. These were based on the needs of the present day Legacy 'Slocum Glider' and vary depending on mission specifications.

Wing placement, angle and shape as well as antenna position and size are major contributors to a smooth glide performance and trawl resistance. Stabilizer fin structures will be pointed down and minimized to avoid snagging in trawl nets and on plant life. A small capture profile is inherent in the shape, and so, to maintain this feature the antenna will be a patch molded flush with the surface of the outer shell.

Propulsion and Navigation

The heart of a gliding vehicle is the buoyancy drive mechanism. There exists a family of buoyancy-drive mechanisms, several of which are currently under consideration: single stroke lead-screw; rotary displacement pump; air compression; and a liquid-to-gas CO_2 conversion. To design a propulsion system that achieves significant buoyancy change for bottom settling, slight buoyancy change for gliding and, perhaps realize pitch and roll steering, The designers have converged upon a buoyancy engine that utilizes a rotary displacement pump to transfer oil from an internal oil bladder to an external bladder. At neutral buoyancy, oil will be in the external bladder. For gliding, a small volume of oil will be moved in and out of an intermediate internal oil bladder providing the required volume change for propulsion (Figure 4).

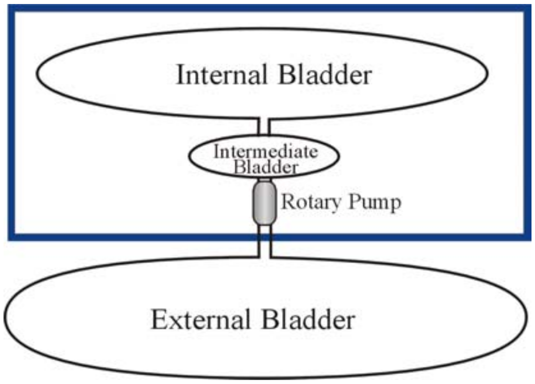

Figure 4 – Diagram of propulsion and bottoming system

Both pitch and roll will be achieved using a mass-shift mechanism; shifting both batteries forward or back for pitch, or side-to-side for roll (Figure 4). Shifting an internal mass laterally in the vehicle will move the center of gravity with respect to the center of buoyancy, causing roll. This roll, in conjunction with the stabilizer fins on the exterior of the vehicle results in steering.

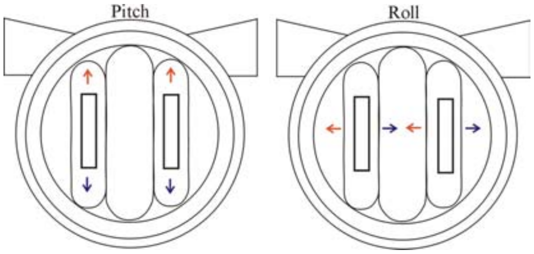

Figure 5 – Pitch and Roll controlled by battery movement

The discus will be capable of full six degree-of-freedom navigation. Heading, pitch and roll will be instrumented with a Precision Navigation TCM2-50, including a magnetic heading compass, which uses correction algorithms to counter the effects of hard and soft iron and is accurate to within one degree. Depth will be measured with a standard analog strain-gage pressure transducer and an altimeter.

Bottom Resting and Release

In order for a bottom-resting vehicle to resist trawls and dredges, it must be capable of maintaining itself on the ocean floor and present a low capture profile. The natural method of maintaining bottom placement is where the vehicle simply becomes heavy. This can be achieved through a large additional buoyancy change in the vehicle. The design is presently advancing towards a limited cycle large displacement system, as this would be more successful in a number of bottom sediment types. Oil from the external bladder will fill a large internal volume (Figure 4), thus making the vehicle heavy and settling it on the bottom. Using the same rotary displacement pump used for gliding, the oil can be pumped back out to the external bladder, adding buoyancy and making the vehicle lighter for liftoff. The low horizontal profile of the discus shape considerably reduces perturbations due to bottom currents and improves settling given negative ballast. Additions to the lower hull, such as shallow concentric rings or low profile studs, may improve bottom attachment.

In addition, there are emerging two overall mission goals for the vehicle in question. One is a gliding vehicle that will fly covertly into an area and plant itself on the bottom as a one-time function. The other is a gliding vehicle that is able to leave the bottom a number of times. The one-time self-propelled, self-placed bottom sensor is an easier vehicle to design, as a volume of the vehicle will simply have to be flooded once. The multi-time bottom lifter will require a buoyancy device that will regain this volume again to leave the bottom. Concepts are converging to a single instrument that will have the option of allowing a bottom liftoff of nominally 10 occasions. To be able to lift off the bottom, the vehicle must once again become positively buoyant by moving the oil back to the external bladder, thus displacing the additional water taken in to settle on the bottom.

Control System Architecture

Given that the discus shape is a poor pressure vessel, the volumetric efficiency is necessarily reduced by stiffeners or by the shell housing a number of cylinders or spheres. The discus glider will differ from a conventional single-hull vehicle where it is possible to have central control architecture with one main interface handling all tasks. An obvious enhancement to the vehicle design would be to block out the usual complement of energy, flight controller, navigation, and communication systems in modular form to allow for placement in a prototype vehicle. Planned is the implementation of a bus system for control communications that reduces the number of routed wires, valuable in reducing underwater connections.

Figure 6 outlines one suggested scheme for modular implementation. The idea behind the concept being that separate controllers exist in the port and starboard hulls, to control all tasks required within the housings and requiring a single, simple connection into the main hull. The primary controller in the main pressure hull performs all system critical tasks such as navigation, steering, communication, flight and sending/receiving information to/from the steering processors. Finally, a separate auxiliary processor will be located inside the main compartment for acquiring, processing and recording science data from available sensors.

This high-speed processor will be operational only for data processing purposes, in support of potential sensors.

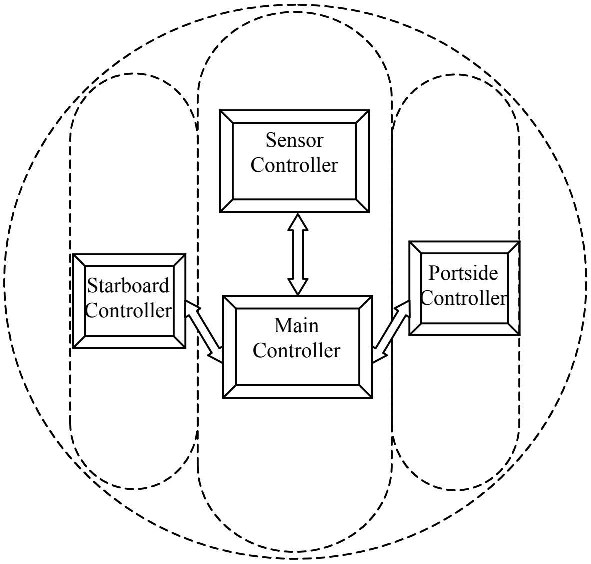

Figure 6 – Preliminary Modular Architecture Block Diagram

Vehicle Hydrodynamics

The ballistics and aerodynamics of the discus, a slight variant in shape from the ellipsoid, have been investigated by Ganslen [10], Rohde [11] and Potts [12]. It was shown that stall occurs at an angle of attack $\alpha = 29^o$. The ellipsoid has a rounded radius while the radius of a discus comes to a sharper edge. Available experimental data [13] shows that the lift to drag ratio is lower than a leading edge wing configuration, however, effectiveness can be greatly improved by horizontal tail wings and a tail fin, that are necessary for stability and control, gliding performance and communication devices. Ellipsoid shapes with stabilizing fins have been tested in wind tunnel tests [14,15,16] for possible use as re-entry vehicles from outer space.

Hoerner [17] lists a drag coefficient for the type of discus thrown in track and field with a thickness to chord ratio (t/c) of 20%. Test data at a Reynolds number of 10^5 gives a drag coefficient (C_d) of 0.08. Comparing this value to a wing section with elliptic cross section, data for a 25% t/c elliptic section at a Reynolds number of 10^5 shows a C_d of approximately 0.08, corresponding well to the discus data in Hoerner. Therefore, using airfoil drag estimation techniques and adjusting variables on which drag is dependent can provide a good estimate of drag on a discus. The drag for a circular discus will depend on the following parameters:

- Thickness to chord ratio
- Ratio of base height to maximum thickness
- Reynolds number
- Surface roughness

Drag coefficient will vary by as much as a factor of 10 for underwater vehicles, depending on the values for the above mentioned parameters. Lift on a discus can be estimated from classical 3D airfoil corrections for aspect ratio. It was shown that for the maximum thickness to chord ratio, the shape has a lift coefficient (C_L) of 0.2 [13]. There is more uncertainty on pitch moment for a discus than for lift and drag.

Much work has been conducted on the aerodynamics of circular flying wings, particularly on spin-stabilized axi-symmetric disc-wings and their potential applications as unmanned air vehicles or guided projectiles. Naturally, extending aerodynamic results to hydrodynamic applications implies the possible and realistic implementation of a circular planform flying wing with stabilizers as an achievable goal.

Note that the discus shape closely mimics that of a ray, specifically designed for gliding and bottom resting, as well as horse-shoe crabs, a species resistant to bottom currents. In addition, the size of the vehicle is comparable to that of a sea-turtle, for which special turtle ejection chutes have been designed into many of today's trawler nets.

Current Status

A model of a discus glider was constructed and flown in a test tank. The model is 36cm diameter and 6.3 liters in volume with a buoyancy drive of 36 grams or 0.6% of displacement (Figure 7a). Buoyancy and weight can be easily shifted on a track allowing adjustments to pitch and steering.

The Discus Glider flew well at a variety of pitch angles (15° to 30°), showed stable turn radius with small rotational changes of the buoyancy drive, and rapid recovery from perturbations.

This model was then ocean tested for glide performance at a depth of 15 ft (Fig. 7b). Three separate tests were performed on the + 30 gram buoyant model. The first tests involved placement of the glider at the bottom of the test area and releasing it to observe lift off and glide characteristics. This yielded smooth take-off and gliding performance to the surface. The second test was to determine mid-water flight and inflection execution. The glider was pushed downwards through the water column at an approximate angle of 25 degrees and released, continuing downwards on its own accord, smoothly inflecting and making its way back to the surface. The third was to shift the buoyancy line from the center (as defined by the tail fin) thereby causing steering as a result of pitch and roll change. All tests were executed using first a set of wings angled at 45^{o} and next a set of wings angled at 90^{o} with respect to the horizontal. Results showed that the 90^{o} wings yielded greater stability and improved flight trajectory. These simple, preliminary tests showed that the discus shape has satisfactory flight dynamics and is a good candidate for a bottom-resting AUV.

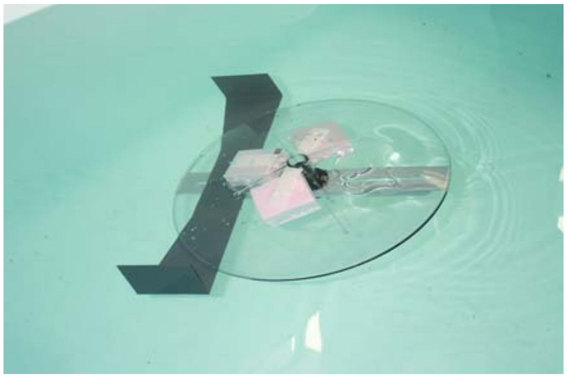

Figure 7a – Model Discus Glider in test tank (90^{o} wings)

Figure 7b – Model Discus Glider in salt water (45^{o} wings)

A model was constructed for scheduled trawl tests run by the Space and Naval Warfare (SPAWAR) Systems Center, Office of Naval Research (ONR) and the National Oceanic and Atmospheric Administration (NOAA) Fisheries in June, 2003. The model measured 24" in diameter, 7" in height and 1/8" thickness hull and was ballasted 10% of the total volume heavy to mimic bottom attachment. The tests involved placing the vehicle on the bottom of the test field and passing over it with a 50 ft shrimp trawler. Divers with video cameras holding onto the nets documented trawl effects. On the first trawl, the vehicle had been in the process of surviving a hit by a trawler door when it was snagged on another object already in the net. For the next trawl, a 2ft tether of 20# test monofilament fishing line was attached to the glider to keep it from drifting due to extreme weather conditions. Figure 8 shows an image of the black model glider with the trawl net passing safely over it. Additional tests were not performed due to the approach of a hurricane.

Figure 8 – Trawl net passing safely over WRC Discus Glider

Numerical analysis of vehicle control, computation of hydrodynamic properties and simulation of in-water gliding are currently in progress.

Future Work

Future projects include flight-testing the models in-water and measuring controlled variables such as glide angle, velocity and buoyancy. Initial goals will be the experimental evaluation of the bottom resting and release techniques outlined previously and improving payload capability. It is expected that the design will undergo several iterations before being finalized.

Acknowledgments

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