UNDERSEA GLIDERS

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ABSTRACT

Undersea gliders offer an alternative propulsion paradigm to the propeller-driven autonomous underwater vehicle by using buoyancy change and wings to produce forward motion. By operating at slow speed (<0.5 ms^{-1}) and being frugal with the electrical power available to the vehicle's control and support systems and sensor payload (typically less than 1 W on average), long endurance can be achieved (over six months, or over 3,000 km). With two-way satellite communications from the sea surface, gliders can send their data ashore and receive new mission commands, enabling powerful new concepts in making ocean observations. Glider missions to date have concentrated on gathering data in support of biophysical and physical oceanography, contributing to studies on ecosystem dynamics, red tides, ocean circulation and climate-related research. Operations have taken place in Polar regions through to the tropics, with hazards including sea ice, hurricanes and vessel traffic. Advances in technology are likely to enable next-generation undersea gliders to travel further, dive deeper, carry more advanced payloads such as chemical and biological sensors and perform in more intelligent or cooperative ways.

1. INTRODUCTION

Some of the earliest undersea gliders were rather similar to their aeronautical counterparts in that they were designed to undertake one profile to depth and then return to the surface. An early trial consisting of 29 dives was conducted in Wakulla Springs, Florida in January 1991 to determine the feasibility of a gliding vehicle [Simonetti 1992]. In Japan, the 1.4m long, 45 kg *Albac* [Kawaguchi et al. 1993] was designed as a one-profile glider with a maximum depth of 300m. It used wings to control its motion through the water on descent, and on reaching its destination depth, dropped a weight to return, gliding upwards to the surface. Another early design was for a tethered free-fall glider designed to make microstructure and turbulence profiles of the ocean mixed layer [Greenan and Oakey 1999]. With a 14° glide slope, speed started at 0.55 ms^{-1} and typically decreased to 0.45 ms^{-1} over a 300 s flight. After reaching its destination depth the glider was recovered via its tether after dropping its 7 kg ballast weight. The low noise and vibration of the glider made it very suitable for measurements of turbulent kinetic energy dissipation rates down to 10^{-9} Wkg^{-1}.

To achieve greater endurance, and to break the analogy with their aeronautical counterparts, glider designs emerged that included a buoyancy-change engine, allowing repeated profiles to be made. In a much-referenced article Stommel [1989] painted a word picture of an ocean observing system using "a fleet of small, neutrally buoyant floats called Slocums [that] migrate vertically by changing ballast, and they can be steered horizontally by gliding on wings at about a 35° angle … Their speed is generally about 0.5 knot". Less well known are the pages in the 1986 notebooks of Douglas C. Webb that show the progression of his ideas on a thermal buoyancy change engine and, two days later, sketches and a numerical analysis for an undersea glider that would use the thermal buoyancy change engine [Webb, personal communication August 2005; Jones et al. 2005]. Webb, the engineer, worked with Stommel, the scientist, to bring these ideas into being. The first trials in November 1991 with an electro-hydraulic undersea glider occurred in Lake Seneca, New York [Simonetti 1992]. Today, there are three well-proven variants using electric buoyancy change: the *Slocum* electric from Webb Research Corporation (Webb et al. 2001); the *Spray* from the Scripps Institution of Oceanography (Sherman et al. 2001) and the *Seaglider* from the University of Washington [Eriksen et al. 2001] (Figure 1). The *Slocum* thermal, although still in an experimental stage, completed a number of missions in the sub-tropical Atlantic in 2005.

These undersea gliders achieve long range despite their small size. This is primarily because they travel at low speed and the power consumption of their control systems and sensors has been carefully minimised. The only essential difference between gliders and propeller-driven underwater vehicles is the mechanism for conversion of stored energy to forward motion. In gliders, electrical energy from the batteries is used by an electric motor within a pump to effect a change in the buoyancy and orientation of the vehicle [Davis et al. 2003]. The change in buoyancy is converted to forward motion with lift surfaces, in this case, wings. In a propeller driven vehicle the motor drives a different type of lift surface: the propeller. While the propeller-driven vehicle can traverse horizontally, the glider is constrained to follow a saw-tooth pattern to achieve forward motion on ascent and descent. Thus, when water column profile data is desired, gliders have an inherent natural motion that is most appropriate.

While the three gliders described above dominate, small laboratory-scale experimental undersea gliders have also been produced, such as the 0.45 m long *Rogue* [Leonard and Graver 2001], designed as a tool to implement and test ideas on vehicle control and dynamics.

Figure 1: Three variants on a long endurance undersea glider, from top: *Slocum* electric, *Seaglider*, *Spray*.

At the Ecole Nationale Superieure D'Ingenieurs in Brest, France a hybrid undersea glider, *Sterne*, has buoyancy control and a thruster for forward propulsion. At 4.5 m long, 900 kg in mass and capable of gliding at 1.3 ms^{-1}, it is larger and faster than the smaller gliders [Moitie and Seube 2001].

2. TECHNOLOGY OF THE VEHICLE AND PAYLOADS

2.1 COMPONENTS

Gliders, as with propeller-driven AUVs, are typically comprised of similar components. Located within a pressure hull are the propulsion mechanics, controller, navigation system, communication hardware, sensors, and energy source. One or more faired wetted areas house sensors, hull penetrators, altimeter and emergency jettison weight. Antennae are mounted externally and arranged to be clear of the water when the vehicle surfaces. While present gliders are centred around the 52 kg mark for ease of handling, the vehicle technology is certainly scalable and can become more volume/drag efficient. There are, however, issues with the additional cost imposed by larger vehicles and the greater handling difficulties. A flying wing glider system with a wingspan of over 6 m is under development (Scripps Institute of Oceanography and the Applied Physics Laboratory – University of Washington).

2.2 HULLS

The family of 6061-T6 aluminium pressure hulls range in shape from cylindrical with a streamlined entry and exit shape (Slocum) to a fibreglass laminar faired shell over an aluminium internally ribbed neutral compressibility shape (Seaglider). A hull with neutral compressibility similar to that of seawater can save pumping energy proportional to the order of dive depth squared [Davis et al. 2003]. This is a useful method of energy conservation as gliders operate to greater depths. Composite carbon fibre hulls are also being brought to bear and can be "tuned" with winding angle, material matrix and by varying wall thickness to accomplish neutral compressibility, with the additional feature over aluminium of reduced material weight. The University of Washington is developing a carbon composite filament wound, low-drag hull that will extend the operating depth to 6000 m [Eriksen, personal communication September 2005].

2.3 PUMPS AND BUOYANCY

Propulsion for gliders is created by changing the volume of the vehicle either by moving oil from an internal bladder to an external one or by pushing seawater in or out of a cavity. By whichever means, the vehicle has maintained a constant mass and changed its volume, thus changing its density relative to the water surrounding it and thereby rising or sinking in the water column. Wings and the body lift of the glider convert this vertical motion to a horizontal displacement in a saw tooth undulation. Hydraulic pump systems, either single stroke or rotary displacement, effect the volume change while overcoming the ambient pressure at depth. A nominal vacuum inside the pressure hull induces the oil to return with a bladder system and in the Slocum the return stroke of the lead screw pulls seawater into a piston cavity. An important consideration is the relative density differences of the stratified water column and the temperature and pressure effects on the volume of the hull. Buoyancy drive force is on the order of 0.5 to 0.9 L displacement for a 52 L vehicle. With such small drive forces, careful attention must be given to preparing the vehicle for the water in which it will be deployed as the difference in overall vehicle buoyancy from oceanic salt water to fresh water for a 52 L hull is 1.4 L.

2.4 CONTROLLERS

The processors in this class of vehicle are typically of very low power consumption and are additionally put into hibernate mode whenever possible due to the stringent energy requirements given the vehicle size and the required endurance. In the case of the Slocum, there is a Persistor flight controller and a separate Persistor science processor in the modular payload bay. Both Seaglider and Spray operate with a Tattletale 8 lower power consumption control computer.

2.5 NAVIGATION AND FLIGHT CONTROL

The primary vehicle navigation system uses an on-board GPS receiver coupled with an attitude sensor, depth sensor, and altimeter to provide dead-reckoned navigation. The Seaglider utilizes a bathymetric lookup table in place of an altimeter, saving its power consumption (i.e. it is preset for a given operating area of the ocean). Steerage is provided by an internal weight shift, as in a hang glider, for both the Spray and Seaglider. The Slocum, optimised for littoral environments, requires a more aggressive turn radius and thus utilizes a tail fin rudder. The overall stability of the vehicles is carefully set up with regards to the *h* moment, defined as the distance between the centre of buoyancy and the centre of gravity, with a typical *h* of 4 to 6 mm. This “tipsiness” or sensitivity to pitch allows the vehicles to adjust pitch by moving a mass, a portion of the batteries, fore and aft to trim the dive/climb angle.

2.6 COMMUNICATION

The present day vehicles all ubiquitously utilize the Iridium satellite phone system for bi-directional worldwide communication. In addition, some vehicles also operate a line of sight RF modem and ARGOS as a backup location and telemetry system. Antennae are located in a tail sting (Seaglider), tailfin (Slocum), and wing (Spray). These are positioned above the sea surface interface while the vehicle is communicating or obtaining a GPS fix. There are automated interface software and hardware sets to handle the incoming calls and outgoing mission instructions.

2.7 SENSOR SUITES

Sensors may be located either external to the vehicle, typically with a drag penalty, within a faired wetted area, or through a port or windowed section of the pressure hull. It is the resulting data that are the driving components of this technology. Fundamentally put, the glider is simply the truck that carries the sensors through the areas of interest and provides storage and communication of data sets. To that effect, each of this family of vehicles has carried a variety of sensor suites depending on the mission. To date there have been physical, optical, and acoustic packages integrated into the payload bay and interfaced with the science controller for data collection. Spray and Seaglider have wetted areas for sensor payload. Slocum is equipped with a 7 L modular payload bay that is capable of carrying a number of sensor suites. Included is a science processor that is interfaced to the flight controller and can be programmed with proglets (akin to functions or subroutines) to easily integrate new sensors. Additional wetted volume is located in the aft cowling. As usual with most AUVs, the goal is develop sensors that provide useful information regarding the ocean and air/sea interface that are small, hydrodynamic, low power, with matched data storage, and affordable.

2.8 ENERGY

Endurance is dictated by the available energy on board and the rate at which it is consumed. Seaglider and Spray both use primary lithium batteries while the Slocum is delivered with alkalines [Davis et al. 2003], although some users have installed their own lithium primary packs. Operations in some high productivity areas are matched well with the endurance achieved with alkalines, as the vehicles have to be recovered within 20 to 30 days for a cleaning to remove bio-fouling. Lithium batteries have a greater energy density and thus are able to extend the endurance or support a greater number of sensors. Compared with alkalines, however, they are considered a hazardous material (UN 3090 Class 9) and thus given the quantity required in a glider, their inclusion means that the glider is more difficult to transport and handle. Lithium-ion secondary batteries are being explored for the rechargeable feature, however, these too, in the quantities necessary to be installed, are classified as a hazardous material. The principal technology needs are for continuing improvement in high capacity energy storage systems.

3. APPLICATIONS

3.1 BIOPHYSICAL AND ECOSYSTEM MONITORING

The Mote Marine Laboratory, Sarasota, Florida and the Coastal Ocean Observation Laboratory of Rutgers University, New Jersey have used gliders to demonstrate the feasibility of obtaining prior warning of offshore blooms of *Karenia brevis*, a toxin-producing dinoflagellate. *K. brevis* blooms are known to drift onshore where they endanger shellfish farms and, within sea spray, the organism is an irritant to the human respiratory system. Such blooms impact the local aquaculture economy, human health and tourism.

At first, the gliders were equipped with a HydroScat-2 sensor for optical backscatter at 676 nm and chlorophyll fluorescence, a non-specific indicator of phytoplankton. In summer and fall 2003, when *K. brevis* blooms were possible, the vehicles were equipped with an Optical Phytoplankton Detector, the so-called BreveBuster, developed by the Mote Marine Laboratory [Kirkpatrick et al. 2003]. Vehicles were directed into areas where satellite imagery had shown elevated levels of chlorophyll.

Beginning in November 2003, the Rutgers University Coastal Ocean Observation Laboratory has deployed 200 m rated *Slocum* electric gliders along a 120 km track on the New Jersey shelf, from 5 km offshore to the shelf break. Their fleet comprised four vehicles and logged over 12,000 km to August 2005 [Jones et al. 2005]. Depending on the instrument package and its power consumption, endurance of an individual mission has varied from 2 – 4 weeks, with each glider in the water for an average of 55% of the year. Instrument payloads have included the standard CTD for temperature and salinity, together with optical instruments including fluorometer, photosynthetically active radiation sensor, multispectral spectrophotometer, optical backscatter and transmissometer for deriving information on biology [Jones et al. 2005]. The data set, available to the public via the web, now includes all seasons, showing summer warming and stratification, upwelling events, mixing during winter and during strong wind events such as Hurricane Ivan in September 2004 (Figure 2).

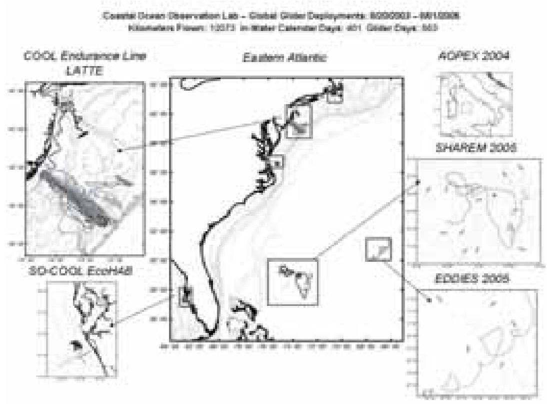

Figure 2: Global glider deployments by Rutgers University's Coastal Ocean Observation Laboratory from 20 August 2003 to 1 August 2005. Total km flown: 12,073; in-water calendar days: 401; Glider days: 563.

3.2 OCEAN CIRCULATION

In a collaborative project between the University of Washington and the Bedford Institute of Oceanography, *Seagliders* were used as a component of an observational array for high-resolution, year-round measurements of volume, freshwater and ice flux variability in Davis Strait. Multiple *Seagliders* provided hydrographic sections across the Strait throughout the year at high spatial resolution.

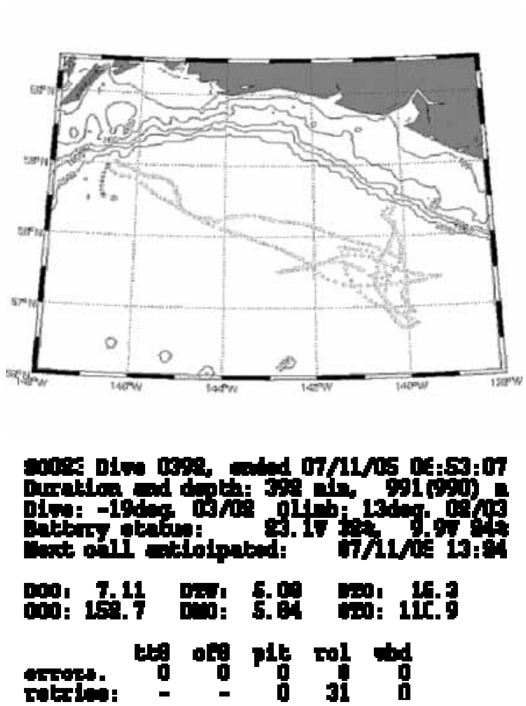

Figure 3: Positions and track of *Seaglider* SG023 up to dive 392 in the Gulf of Alaska, together with summary data on vehicle status on 7 November 2005. [from Seaglider 2005].

Temperature, salinity and density data from the gliders, combined with current data from moored ADCPs produce estimates of absolute geostrophic velocity, volume transport and freshwater fluxes. Summary information from the *Seagliders* is made available on the web in near-real time [Seaglider 2005]. An example from a deployment in the Gulf of Alaska is shown in Figure 3.

Out of 22 *Seagliders* built prior to September 2005, 12 remained available for use, ten having being lost [Eriksen, personal communication September 2005]. As examples of maximal deployment endurance, one *Seaglider* mission covered 3,200 km in six months, one week, while another covered 3,750 km in seven months, one week.

Although gliders may not always be able to navigate a pre-set course when operating in areas where the depth mean current exceeds their forward speed, useful information can nevertheless be obtained. A *Spray* glider, in a joint experiment between the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution, was deployed on the shelf slope south of New England in September 2004 with waypoints set on a course to Bermuda, entailing a crossing of the Gulf Stream [Spray 2005]. The mission length was 1,000 km. Figure 4 shows the track of the glider together with measured mean current over the upper 1,000 m. The glider's nominal track was affected dramatically by the Gulf Stream meanders, with depth-averaged currents in excess of 1 ms^{-1}. Despite this, the glider was able to cross the Gulf Stream.

Assessing the technology readiness of undersea gliders as long-range, reliable multidisciplinary sensor platforms was an objective of the EU MERSEA (Marine Environment and Security for the European Area) project. The first deployment of a 1,000 m *Slocum* electric glider with user-fitted primary lithium batteries for extended endurance, in support of this assessment, was off Mallorca in the Mediterranean Sea in September 2005.

For one week, the glider was used in a virtual mooring mode, collecting 130 profiles to 1,000 m [MERSEA 2005, Figure 5].

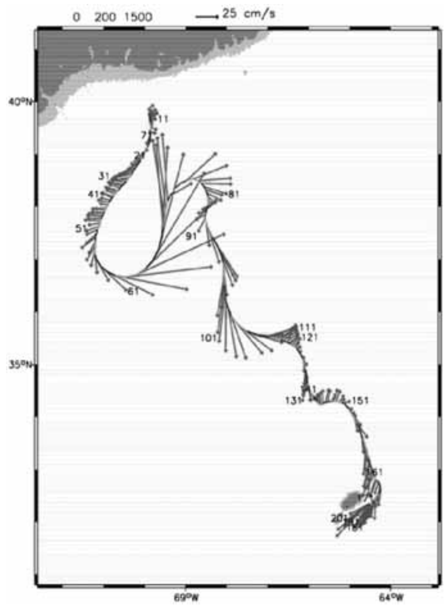

Figure 4: Trajectory and ocean current vertically averaged from the surface to 1,000 m for a *Spray* glider deployed in September 2004 from the New England shelf on a transit to Bermuda [from Spray 2005].

3.2 DEFENCE AND SECURITY

The US ONR (Office of Naval Research) has provided the funding that has brought glider technology to life with a push to exploit the endurance, water column undulations, and inherent quietness of the platform. Undersea gliders are capable of transiting from over the horizon, performing an assessment of environmental parameters and transmitting the data to a command/control centre. Several glider-borne optical package suites have been demonstrated to aid in MCM (mine counter measures) by determining the visibility in littoral areas in advance of deployed assets [Jones et al. 2005].

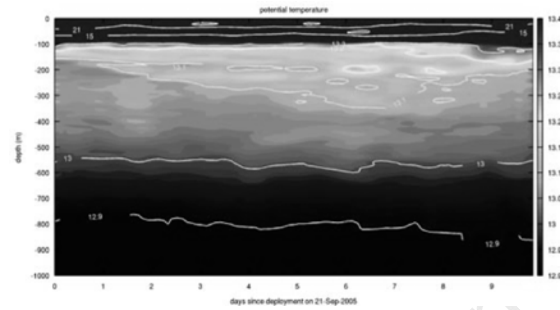

Figure 5: Temperature data from a 1,000 m Slocum electric off Mallorca, operating in virtual mooring mode in September 2005 [from MERSEA 2005].

Without a propeller, the vehicles have proven to have low self-noise and are good candidates for acoustic packages. Slocum Gateway gliders equipped with acoustic modems collect and relay data sets from ocean floor sensor nodes to a control centre via satellite or radio link. In addition, passive acoustic recording devices have been used to triangulate whales and to provide a "bell ringer" capability to identify high speed surface craft. Recently, a 30 m long array was towed by a Slocum with onboard recording capabilities.

The three main glider groups have participated in a variety of demonstrations and exercises with multiple vehicles working in a coordinated and adaptable effort providing depth averaged currents and sound speed profile data. With a number of gliders covering a temporal and spatial scale, users are able to overcome the gliders' lack of speed by cooperatively filling in areas of environmental uncertainty. Navy modellers are then presented with a greatly enhanced data set to assimilate into prediction routines [Jones et al. 2005]. The capability of launch and recovery from a variety of vessels from rigid inflatables to 100 m ships has been put into operation. Aircraft deployment of the gliders is on the project list and a Slocum has been released from a submarine.

4. DISCUSSION

The technology of undersea gliders is becoming accepted by the wider science community, not just by the developers. There is presently a transition from the adolescent stage to one of operational use and maturity with an expanding user group. The definition of operational oceanography as "sustained data collection or modelling efforts that include real-time distribution of useful products to a larger community, scientific or otherwise" [Glenn et al. 2004] insists on getting the technology and resulting data into the hands of others.

With this comes the necessity of infrastructure for maintenance, repair, training and customer service. New user groups bring with them new applications for the platforms and the sensors to be integrated - constantly expanding the role of the vehicle. There is no monopoly on glider technology, multiple sources are available and competition is helping to drive innovation, customer service and reliability for those who wish to purchase vehicles. Given an oceanographic worldview, the future holds that there will be relatively large numbers of gliders operating in fleets providing ground-truth for satellites, complementing shipboard activities, and filling gaps between moorings or becoming virtual moorings themselves.

Today, even with the low-ish numbers of gliders that have been built to date (over 100), gliders are cost effective both in capital procurement and cost of operation. "In perspective, gliders can collect several multivariable (e.g. temperature, salinity, velocity, oxygen, fluorescence, optical backscatter, etc.) profiles for the cost of a single expendable bathythermograph (XBT) probe." [Davis et al. 2003]. This is a major accomplishment that is not often found in the AUV market, particularly, without yet, the economy of scale that goes with greater production and the enhancements as the platform transitions from prototype to consumer product. As with other AUVs, the glider business must use products developed for larger markets, for the oceanographic market is not large enough to drive component price down on its own. Beyond the technology are the legal and liability issues. Even within the limited numbers discussed here, as more ocean research platforms are in operation, collision avoidance and international agreements on operating practice may become areas of concern.

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