Autonomous Underwater Glider Research at Memorial University

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Autonomous Underwater Gliders (AUGs) are becoming the tool of choice for oceanographers to collect in-situ data on the world's oceans. Since the summer of 2006, the National Research Council-Institute for Ocean Technology (NRC-IOT) and Memorial University (MUN) have been exploring the potential for AUGs to gather oceanographic information with application to the Newfoundland Shelf. Our group has now collected over a month's worth of deployment data, and has flown over 700 km with AUGs. Preliminary work has involved testing these vehicles in our local environment and also the integration of new sensors into the platform.

A Definition of Ocean Gliders

A glider is a type of autonomous underwater vehicle (AUV) that is able to move for weeks or even months unattended through the oceans, collecting valuable data on its way (see Figure 1). Gliders "fly" through the water similar to a soaring plane in the air. Unlike their atmospheric counterparts, underwater gliders can change their weight in the water from negatively buoyant to positively buoyant,

Figure 1: A Slocum glider deployed in Conception Bay, NL.

therefore allowing for not only downward motion but also upward motion, resulting in their characteristic “saw-tooth” flight pattern (Figure 2). However, the amount of buoyancy change is limited to about 0.5% of the gliders’ overall weight, resulting in a small driving force and a modest advance velocity; this makes a glider more like a soaring blimp than a plane. The buoyancy engine is the device that changes the buoyancy of the glider from negative to positive and vice versa. For deeper gliders, this is usually a high efficiency pump, while for the shallow water gliders a piston drive suffices.

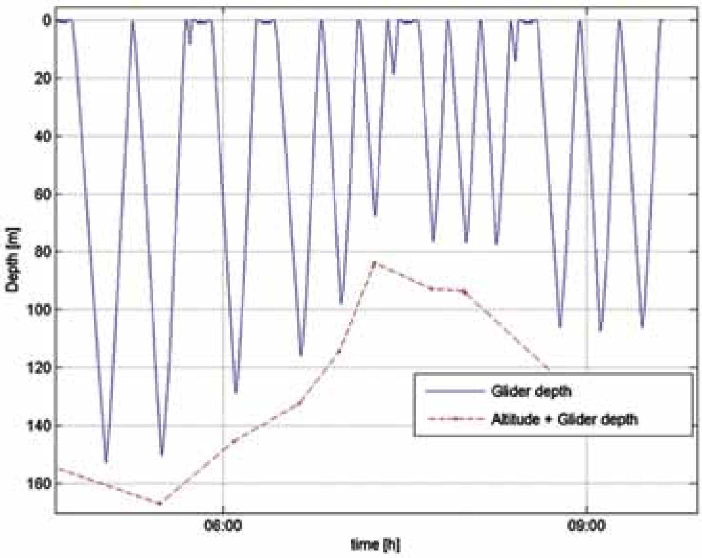

Figure 2: A Slocum glider travels in a saw-tooth pattern. Here we see several "yo's" in blue. A single yo consists of one downward glide and one upward glide; several yo's can be concatenated before the glider comes to the surface. The red line shows the depth of the bottom as determined by the Slocum’s altimeter.

There are currently four glider systems commercially available. The different models are similar in size but vary in maximum depth capabilities, endurance, sensor payload, communication and navigation options. The existing systems are the Slocum glider family, consisting of a shallow 200 m and 1000 m electric driven glider, the SPRAY 1000 m glider (Bluefin Robotics), the 1500 m SEAGLIDER (iROBOT), and the 800 m SeaExplorer (ACSA).

For our research, we are using the shallow 200 m Slocum glider. (See Table 1 for a summary of the approximate dimensions of the Slocum glider.) Note that the above mentioned buoyancy change capacity of 0.5% is significantly less than the density difference between fresh and salt water, thus the glider is unable to compensate for the full range of density gradients that may occur, making an exact ballasting procedure necessary.

Dimensions	Length ~150 cm Diameter ~21 cm
Speed	~35 cm/s
Depth	4-200 m
Endurance	~30 days
Power	Alkaline Battery
Weight	52 kg
Range	~1500 km

Table 1: Specifications of the Slocum battery glider.

The glider has three communication options: a line of sight high bandwidth RF-modem; a global satellite phone modem; and an emergency ARGOS transmitter as a backup in the event of equipment failure.

The glider determines its position at the surface using a GPS receiver. While submerged, the glider uses ded-reckoning to keep track of its estimated position. The vehicle calculates its desired heading between its current position and the next waypoint. The heading together with the measured attitude and the rate of change of depth allows the glider to compute an estimated position. In the absence of external disturbances, such as subsurface currents, a well-trimmed glider would fly straight and would arrive at its desired waypoint. However, due to the existence of subsurface currents and inaccuracies in trim and control, the glider needs to verify its position at predetermined intervals using GPS at the surface. Figure 3 shows a schematic of how a glider navigates between two waypoints. Once the glider is at the surface, it always tries to establish communications with the control centre using the global satellite phone and the RF-modem. Once communication is established, all mission parameters can be changed if desired, otherwise the glider continues to execute its currently loaded mission.

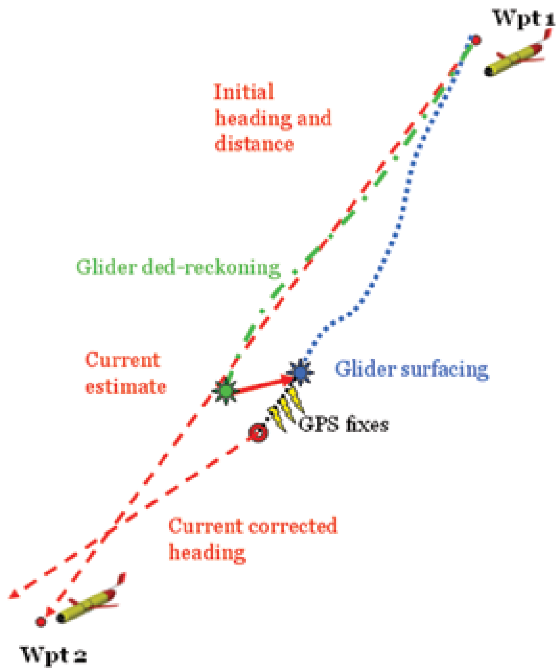

Figure 3: The glider navigates using ded-reckoning. The green line represents the ded-reckoned path while the blue line depicts the actual path. When the glider surfaces, it uses an estimate of the depth-averaged currents over the past yo, combined with surface drift, estimated from the GPS, to determine its next heading.

Mission Planning

Ballasting the glider to ensure it is neutrally buoyant in its sampling area is an essential part of planning a glider mission. The buoyancy engine can ingest or expel only 250 cm^3 of surrounding fluid. This means that the mass of the glider can only change by about +/-250 g, or +/-0.5%, of its total mass. With such a limited range of mass change, it is crucial that the vehicle be pre-ballasted to the density of the seawater in which the vehicle will operate during its next mission. In addition to the overall ballast, the glider has to be trimmed for roll, pitch and overall stability. While pitch and roll are corrected by moving masses in the horizontal plane, the overall stability is adjusted by moving weights in the vertical plane. The principle of stability correction is similar to that of a sailboat with a keel. The lower the centre of gravity in the glider, the more stable the system becomes, and the more it resists disturbances in pitch and roll. However, it cannot be too stiff since it would resist the glider's desired pitching motion that enables forward flight.

There are also many environmental and other system factors to consider when preparing the glider for deployment. The horizontal speed of the Slocum relative to the surrounding water is typically around 25-35 cm/s; therefore, areas of strong current must be avoided. Also, the efficiency of the trajectory of the glider depends on the mechanical and electrical efficiency and duty cycle of the buoyancy engine (i.e. the longer and deeper the glide, the smaller the duty cycle and hence the lower the power consumption). Because of this, the Slocum should be limited to areas where it can achieve its full dive depth of approximately 200 m to conserve battery power.

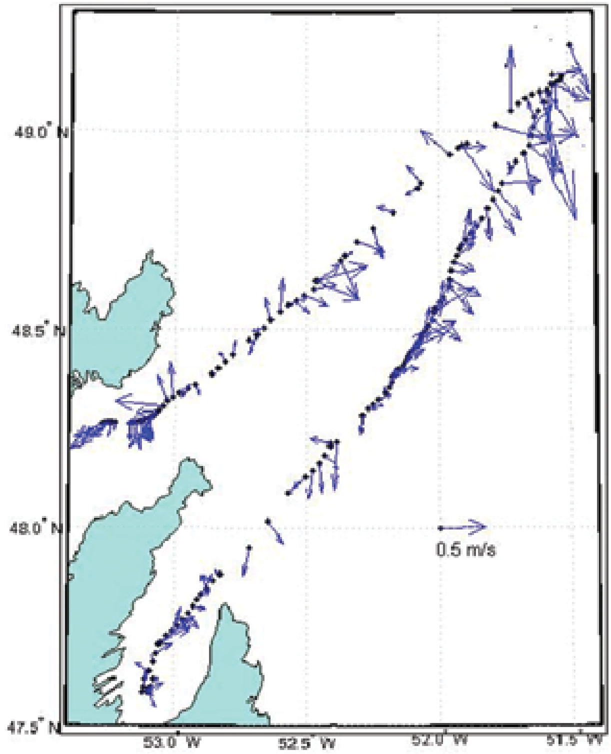

Figure 4: Examples of surface currents computed from GPS fixes while the Slocum is transmitting data. The largest velocities correspond to where the glider crossed the inner branch of the Labrador current.

Other aspects of mission planning include but are not limited to 1) creating a set of waypoints that the glider will navigate between, 2) choosing which sensors will be turned on, 3) choosing whether to sample on the upcast, downcast, or both, 4) setting maximum upper and lower climb depths, 5) determining how often to surface for satellite communication, and 6) determining which sensor data to transmit while surfaced.

Data and Distribution

Several different types of scientific data can be collected by the Slocum. Typically the gliders carry conductivity, temperature and depth sensors (CTD), which are the fundamental variables for understanding oceanic processes. Recently, our research group installed an Aanderra Oxygen optode sensor, which measures oxygen concentration and saturation. The Slocum also offers us two different estimates of ocean currents: a depth-averaged current, based on ded-reckoning and hydrodynamics of the glider, and also a surface current (Figure 4), which is calculated using the vehicle's drift at the surface while transmitting data. Besides the scientific data, we also have access to engineering data, which can be used to better understand the operation of the vehicle itself. In addition to other internal variables, the Slocum records heading, pitch, and roll, along with internal temperature and pressure.

During glider deployments, new data are received on each surfacing, typically every few hours. A web page was created specifically for presenting the data collected from the glider missions (www.physics.mun.ca/~glider/). A suite of Matlab scripts was written to aid in the analysis and distribution of the data. These scripts were designed to automate the process of examining data; however, more in-depth analysis of the data is left to the researchers. The benefits of using automated scripts to analyze and store the data online are evident as it allows researchers not directly involved with deployments access to near-real-time data from anywhere via an internet connection.

The Role of Ocean Gliders

Gliders being small, smart, and inexpensive instrument platforms offer the ability to sample the ocean with much higher resolution in space and time than is possible with techniques reliant on ships and moorings. The primary purpose of AUGs is to complement traditional ship sampling by providing a higher horizontal resolution in the along-track direction. A real benefit to this small platform approach is that the infrastructure is scalable – gliders are readily portable to sample phenomena that may be intermittent and localized, such as mixing and upwelling events, and phytoplankton blooms.

Deploying a glider can be done very easily by two people and has a much lower cost associated than ship sampling ($75,000 to purchase a glider versus ~$10,000 for one day of ship sampling). Perhaps one of the greatest advantages of gliders is their ability to adaptively sample based on real time data collection. Ships too can have flexible scheduling, but are too expensive to have out on regular patrols. Ships, on the other hand, are not limited by depth, provide very high vertical resolution, and are faster than AUGs. Gliders, however, are not affected by weather (one of our deployments occurred during hurricane Issac in 2006 with no associated problems).

Field Deployments

We have conducted six main test deployments with the Slocum glider; see Table 2.

Mission	**Date**	**Location**	**Duration**	**Distance covered**	**Purpose**
Tethered Test Deployments	Spring 2006	Conception Bay, NL	~2 days	~2 km	Initial testing of glider systems
Operational Test	July-August 2006	Trinity Bay to Conception Bay, NL	20 days	550 km	Comparison of glider data to ship-based survey
Optode Test	September-October 2006	Conception Bay, NL	6 days	211 km	Testing of a dissolved oxygen sensor
Calibration Test	Fall 2007	Conception Bay, NL	1 day	2 km	Verification of developed correction algorithms
Acoustics Test 1	Summer 2007	Ilulissat Fjord, Greenland	~2 days	~2 km	Testing of Ice-profiling sonar
Acoustics Test 2	August 2008	Conception Bay, NL	1 day	N/A	Testing of Nortek ADCP

Table 2: Deployments of the Slocum glider from 2006 to present.

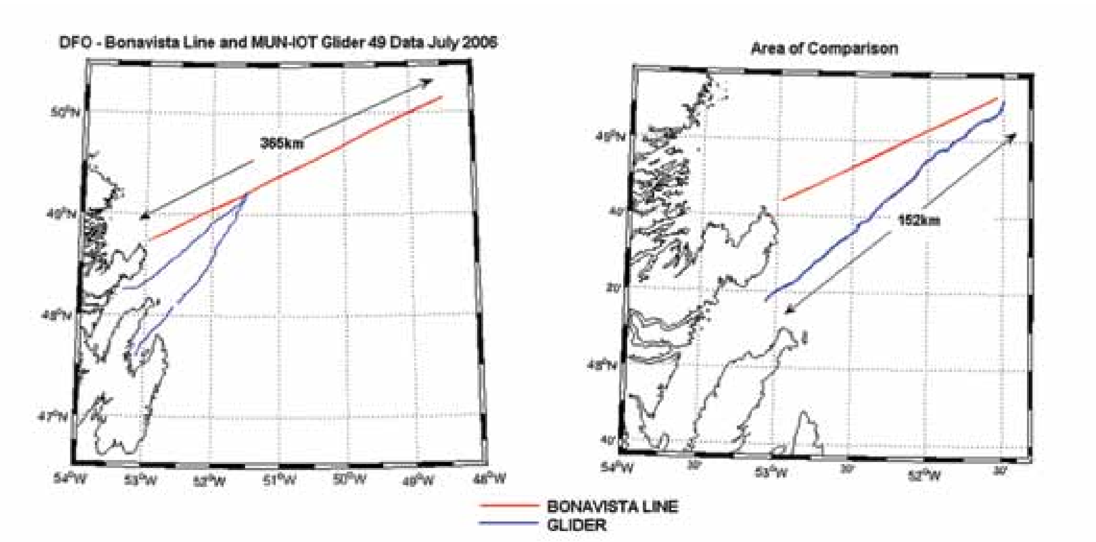

Figure 5: Our first major deployment was carried out to coincide with data collected from the Canadian Department of Fisheries and Ocean's Bonavista line.

Operational Test

Our first major deployment of the Slocum was in July of 2006. The purpose of this mission was to assess the operational abilities of the glider in the strong currents off the coast of Newfoundland, over the continental shelf. This deployment had a CTD onboard, with no additional sensors. The track of the glider was out through Trinity Bay and across the continental shelf, cutting across the inner branch of the Labrador Current. In choosing this route, there was some concern that the glider might have difficulty flying against the strong currents (which can easily exceed 30 cm/s in the mixed layer). While the currents did slow the glider down at points, it was able to complete its mission successfully. This specific track was chosen so that it would overlap with data collected by the Canadian Department of Fisheries and Oceans surveying the Bonavista line, part of the Atlantic Zone Monitoring Program (AZMP). About 360 km long, the Bonavista line (Figure 5) takes about 20 hours to steam in a ship and would require, for 15 stations, about 15 hours of station time (~ a day and a half). For comparison, a glider would take about two weeks to cover the same line, seven days out, seven days to get back.

A comparison of temperature data obtained from both the glider and the AZMP (Figure 6) shows that the glider collects nearly 10 times more data points in the upper 200 m than is available from the traditional ship-sampling. Horizontal resolution of the glider data is ~0.5 km while the ship-survey is 15 km.

Optode and Calibration Test

Our second deployment occurred in Conception Bay, Newfoundland, lasting a total of eight days, with the primary purpose of testing a newly installed Aanderaa Instruments dissolved oxygen sensor: the oxygen optode 3835. The optode was integrated into the glider in the flooded area in the tail while being exposed through a small 5x5 cm hole that we cut in the tail-fairing of the glider. The resulting data analysis from this deployment revealed sensor dynamics issues with the optode – the raw data recorded contained a large offset between the downcast and upcast due to the instrument having a rather large response time of about 20 seconds. Correction algorithms were then developed to correct for these response issues.

We conducted a second deployment with the optode combined with an independent

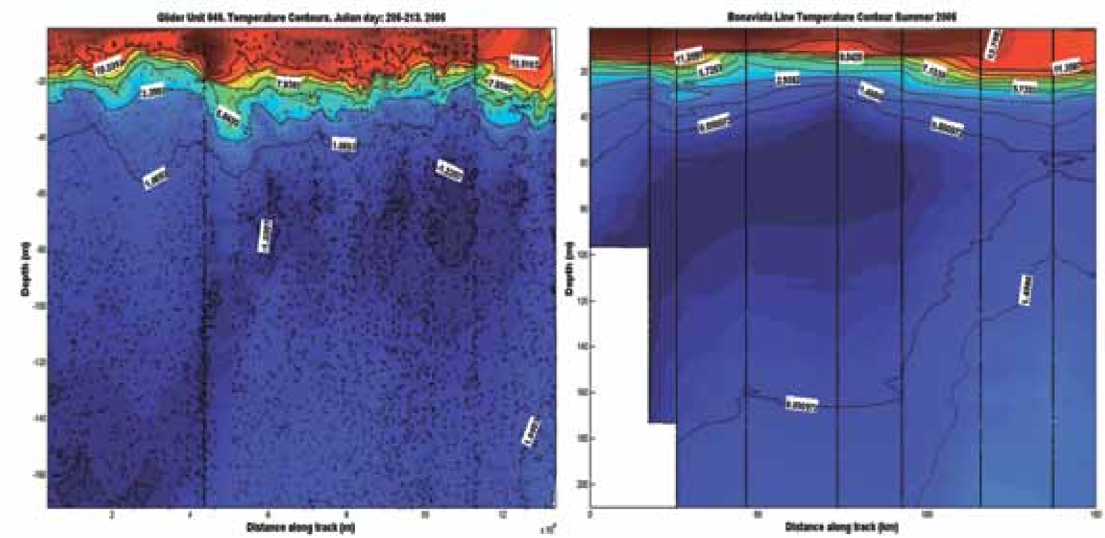

Figure 6: (Left) Temperature data collected by Slocum glider. (Right) Temperature data obtained from traditional ship survey. The black x's mark individual sampling locations. There are approximately 10 times more data in the left figure than in the right.

measuring device – a SBE43 oxygen sensor. The SBE43 sensor was lowered from a ship in the same geographical area where the glider was sampling. By having an independent data set, we were able to test and verify our correction algorithms and create a new working calibration for the optode.

With the addition and calibration of the oxygen optode, the glider now has the ability to measure dissolved oxygen, which is involved in most biological and chemical processes in aquatic environments. Dissolved oxygen can also be used as an oceanographic tracer to follow specific water masses.

Acoustic Instrumentation Testing

In the summer of 2007, researchers from MUN and the NRC joined an international team in Ilulissat, Greenland, to use AUGs in the study of the factors influencing glacial melting and advance. The glider's altimeter was used as an upward looking ice profiling system to allow the glider to travel underneath icebergs, and eventually, under the outer edges of glaciers, essentially mapping them as they moved along. While the surface of glaciers can be studied with the use of satellites, relatively little is known about the bottom. The integration of the ice-profiling sonar is a key step towards our objective to develop a long-range autonomous ice-profiling capability using underwater gliders. Since the initial deployment using the modified altimeter of the glider, a dedicated 600 kHz ASL ice-profiling system has been integrated and awaits its deployment early next year.

We have begun the integration of a 400 kHz 3-beam Nortek Aquadopp Profiler into the Slocum glider. This Acoustic Doppler Current Profiler (ADCP) measures the 3-dimensional current velocity field, along with backscatter of particulates in the water column. In our initial deployment, a 300 kHz BroadBand Workhorse RDI ADCP was deployed in an upward looking moored mode to provide calibration data to determine range and data quality of the glider based ADCP (Figure 7). The next step in this integration is to examine how the hydrodynamics of the glider may have changed due to this additional sensor.

Future Plans

One key drawback of adding sensors to the glider is the increase in power consumption,

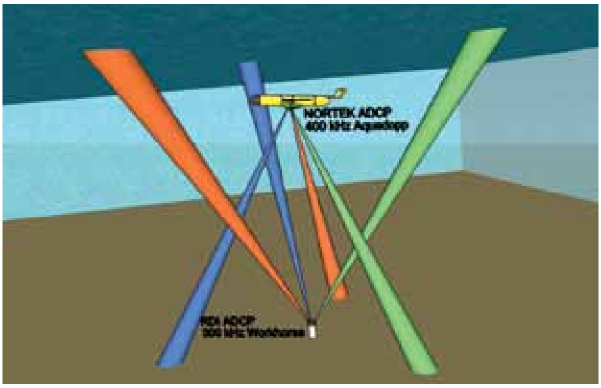

Figure 7: Initial testing of the Nortek ADCP integrated into the Slocum glider. The glider was deployed over a moored ADCP for calibration purposes.

and therefore a reduction in mission length. Frequent communication and shallow dives (which imply frequent use of the buoyancy engine) also contribute to reduced mission length. Special consideration has to be given to the sensor choices with respect to size, power, and frequency. A balance must be considered between how much data we can collect and how long we wish to sample for. How often and what types of data should be communicated back? Should we sample data on the downcast only? We must study different sampling regimes and determine the most balanced approach between collecting as much data as possible, and operating the vehicle for as long as possible. One possibility for increasing the power available and also decreasing the weight of the glider would be to upgrade the alkaline batteries to lithium-ion.

The glider is inherently limited in its sampling environment by its slow horizontal speed through the water; we cannot deploy in areas of strong currents. Also, areas with strong fluxes of freshwater, near melting glaciers for example, provide a challenge for the glider to surface as there are caps of less dense fluid sitting on top of denser seawater – such a large gradient in density is outside the glider's buoyancy engine capabilities. The addition of an active propulsion system could increase the vehicle's forward speed, which would allow it to fly in areas of stronger currents, and also to breach the surface in areas of strong density differences.

A prototype auxiliary propulsion system has been designed and built that uses a high efficiency, low power motor. It is coupled to the propeller through a magnetic coupling to minimize frictional losses from rotary shaft seals. This system currently is undergoing laboratory testing and is scheduled for a test-deployment in spring 2009.

The goal of the ADCP integration is to provide absolute current velocity profiles over the entire 200 m dive envelope of the glider. The regular profiling range of this profiler is between 60 to 90 m so it will not provide the full 200 m range that we seek. We need to develop a bootstrap sampling protocol in which we can use overlapping sampling windows to extend the sampling beyond the standard range of the 400 kHz system.

Conclusions

Autonomous vehicles offer enormous potential for extending our sampling reach into the oceans. Gliders have distinct strengths, in particular, their ability to sample in the vertical direction and their endurance, but also weaknesses, for example, their limited electrical power capacity for additional sensors. These vehicles represent a large cost-savings when compared to traditional sampling and no longer limit a researcher to the constraints of a surface vessel.

Charlie Bishop is a PhD candidate in physical oceanography at Memorial University of Newfoundland. He received his Bachelor of Science in physics in 2006, followed by a Master's in Science in environmental science in 2008. Currently his doctoral research interests are focused on the dynamics of newly integrated sensors on autonomous underwater vehicles and their application to collecting oceanographic data on the Newfoundland shelf.

Dr. Ralf Bachmayer currently holds the Canada Research Chair for Ocean Technology in the Faculty of Engineering and Applied Science at Memorial University. His research is focused in the area of the design, dynamics and control of underwater vehicles and underwater gliders. His particular interest is to expand the capabilities of underwater platforms to explore remote regions such as the Canadian Arctic.

Dr. Brad De Young is the Robert A. Bartlett Professor of Oceanography at Memorial University and the Chair of the Department of Physics and Physical Oceanography. He works on the observation and modeling of physical and biological processes in the ocean. His geographic window on the ocean is the Northwest Atlantic. Brad is particularly interested in developing new instrumentation and new approaches to observing the ocean.