The State of Technology in 2013
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State of Technology in Autonomous Underwater Gliders

AUTHORS
Stephen L. Wood
Florida Institute of Technology
Cheryl E. Mierzwa
Bluefin Robotics, Quincy, Massachusetts

ABSTRACT
Over the last few decades, a range of instruments and vehicles have been used to monitor the oceans. One example is the use of autonomous underwater vehicles to perform ocean surveys, and within this group, autonomous underwater gliders have made their mark. Gliders enable the scientist to make extended complex studies on topics such as the effect of metals, pesticides, and nutrients on fish abundance, reproductive success, and ability to feed on contaminants such as chemicals or biological toxins that are transported in particulate form and may become incorporated into living organisms (plankton, bivalves, and fish) or become deposited in bottom sediments. With these vehicles, the scientist or environmentalist can detect hazardous substances in the ocean such as chemicals from an oil spill or toxic algae such as red tide.

Keywords: autonomous, AUV, gliders, Lagrangian, Slocum, underwater, vehicles

Introduction

Autonomous underwater gliders make up the newest field of underwater vehicles. These vehicles glide through the ocean at low speeds using changes in buoyancy to ascend and descend while their wings generate lift to propel them forward. These gliders conduct long-duration missions to acquire and communicate scientific data to researchers throughout the world without direct involvement of ships or personnel. With their slow glide speeds, they are deployed longer and for greater distances than standard powered autonomous underwater vehicles (AUVs). Consequently, gliders have become extremely valuable for long-term, large area, and deep-depth oceanographic sensing missions of the ocean.

Protecting the ocean is essential to future generations. Acquiring data directly at depth with high temporal and spatial resolution is necessary in order to continuously monitor and analyze ocean trends; learn about ocean processes; predict climate change; and acquire physical, biological, and oceanographic data (Davis et al., 2003). Currently, oceanographic data are gathered via different forms of remote sensing, deploying oceanographic instruments from ships and through the use of AUVs. Since remote sensing is limited to the ocean surface and deploying instruments aboard ships is very costly and time consuming, AUVs are widely used for data collection.

The more information scientists are able to accumulate, the better they will be able to determine the health of the ocean ecosystem and document the specific ecosystem parameters. Using an AUV glider, scientists can detect and quantify in an automated way various substances or phenomena; depending on the glider, water samples can be taken and analyzed to determine water quality as well as any contaminating chemicals. Thus, dangerous substances in the sea can be detected earlier, and their harmful effects can be dealt with quicker.

The AUV shown in Figure 1 is a propulsion-driven underwater vehicle that uses a propeller to move. Similarly, the autonomous underwater gliders in Figure 2 are low-power AUVs that use buoyancy changes for vertical movement and wings for horizontal movement to propel the glider forward. A glider is an easy and affordable way to acquire continuous data such as conductivity, temperature, depth, dissolved oxygen, and turbidity throughout the water column. Because gliders are small and low-power vehicles, they are able to log data up to months at a time and with minimal dependence on large ocean vessels.

FIGURE 1
Florida Tech’s Bluefin battlespace preparation AUV.
During a mission, gliders can operate in harsh deep-ocean and coastal aquatic environments. They are able to circle an area of interest, wait at the bottom of a glide path for long periods of time, and quietly move undetected. Gliders have little impact to the environment and provide minimum threat to sea creatures because of their slender body and slow movement through the water. The characteristics and feasibility of gliders has led to a high interest in glider research at various institutions for oceanographic data collection, experience, and testing.

Gliders are primarily designed for deep water where the vehicle can traverse large areas with minimal use of energy and are specifically designed for the needs of the “Blue Water” scientist (Argo, 2013). Some of these glider AUVs have space for multiple scientific instruments and have the ability to obtain water or biological samples. Scientists who perform experiments in shallower water can also use the vehicle for short-duration gliding dives or under power if one of the hybrid gliders is used.

The general performance characteristics of standard underwater gliders are similar, but new hybrid systems and surface ocean wave-driven gliders are a new anomaly to the glider field. Gliders in general are excellent at the tasks they are designed to do (i.e., very long term, very little power, slow cruising of the ocean’s water column), but they are limited as to the type of payloads they can carry, and they typically have no active propulsion for times that require more than buoyancy thrust (e.g., control of the vehicle at the surface). These autonomous underwater gliders each change their buoyancy to be able to travel horizontally in the ocean’s water column using the lift on their wings, like a normal glider does to convert vertical velocity into forward motion. These vehicles are not capable of traveling in a horizontal path as would a typical propeller vehicle but follow a sawtooth path as the vehicle descends or ascends.

The original underwater gliders were designed specifically for long-term sampling and easy deployment and recovery by a minimal crew (i.e., one to three people) on any size boat or ship (vessel of opportunity). Consequently, this requires a design that has minimal space for instrumentation and is limited in its function/capabilities. These vehicles are relatively inexpensive, costing less than a week and a half of ship time for a research vessel.

As a group, most gliders can achieve four basic sampling modes: (1) vertical sampling where the forward motion of the vehicle counters any local currents to maintain position, (2) horizontal sawtooth sampling where the forward motion allows for the vehicle to obtain information both vertically and horizontally, (3) array sampling where multiple gliders form a distribution of sampling instruments covering an entire region, and (4) long life and repeated sampling over an extended duration.

History and Development of Underwater Gliders

The concept of underwater gliders was pictured first by Henry Stommel in 1989 when he envisioned a group of underwater floats called “Slocums” capable of moving vertically and horizontally in the water returning observations of the changing state of the ocean (Sherman et al., 2001). His vision led to the design of buoyancy-driven floats that turned into the development of underwater gliders.

Buoyancy-Driven Float

The Autonomous Lagrangian Circulation Explorer (ALACE) buoyancy-driven float shown in Figure 3 resulted from Stommel’s idea. This float alternates between drifting and profile modes to acquire data directly at depth to gain an understanding of ocean dynamics (see Figure 4).

The ALACE float, along with the Profiling ALACE (PALACE) and Salinity Profiling ALACE (S-PALACE), is part of the Argo network, which is a global array of profiling floats that began deployments in 2000, totaling 3,633 floats as of October 1, 2013. These floats stay out for months capturing data with temperature, salinity, and current sensors and sending data back to shore through a satellite link to the Argo network (Argo, 2013).

Current glider buoyancy systems originated from a method similar to the buoyancy system on the ALACE.
float known as the Leduc ballast system. This system contains an extruding piston that moves in and out of the bottom of the float by a motor-driven lead screw system. With a known volume change, the float can change from negatively to positively buoyant and move throughout the ocean. The float uses an ORBCOMM satellite uplink to transmit data, receive instructions, and allow scientists to obtain semi real-time observations to estimate the climate system and observe the physical state of the ocean (D’Asaro, 2003).

Buoyancy-driven floats have the advantage of mobility and low manufacturing costs. The disadvantage for floats is the lack of position control. Currents have a major influence on float location, and the float is unable to correct its position, speed, and direction. Due to the need for control, underwater gliders were designed to provide a control system, a navigation algorithm, and a low drag vehicle with appendages to observe all areas of the ocean (Skibski, 2011).

**Current Underwater Glider Designs**

There are currently four classes of underwater gliders: (1) those that use mechanical or electrical means of changing their buoyancy (i.e., drop weights or electrical power from batteries), (2) those that use the thermal gradient of the ocean to harness the energy to change the vehicle’s buoyancy, (3) those that are able to use other means of power such as ocean wave energy, and (4) hybrid vehicles that use standard propulsion systems and glider systems.

The present-day commercial gliders include the University of Washington’s Applied Research Laboratory and Kongsberg Maritime’s Seaglider, Teledyne Webb Research’s Slocum Electric and Thermal Glider, Scripps Oceanographic Institution, and Bluefin Robotics Corporation’s (2013) Spray Glider. The design, development, and first sea trials of these gliders started in the early 1990s using the ALACE float technology.

- 1970: Sound fixing and ranging floats were developed to measure ocean currents (Richardson, 2006).
- 1991: Spray Glider performed preliminary lake tests (Sherman et al., 2001). A prototype was designed and tested for the Slocum battery-powered glider in Wakulla Springs, FL, using an autopilot and flight recorder (Webb et al., 2001).
- 1995: Webb Research Corporation tested the hull of the Spray Glider...
(Sherman et al., 2001). A vertical profiling vehicle powered by thermal propulsion was deployed in the Sargasso Sea (Webb et al., 2001).

- 1998: A glider and thermal engine were deployed at Seneca Lake, NY, with a thermocline (Webb et al., 2001).
- 1999: First spray sea trial with the autonomous ocean sensing network experiment in the Monterey Underwater Canyon. Spray was recovered 11 days later with 182 logged temperature and conductivity profiles (Sherman et al., 2001).
- 2004: Seaglider’s launch in the North Pacific Ocean and recovery at the shore of Kauai, Hawaii (University of Washington, 2013).

Common Features of Current Designs

Features that are common to each of the three commercial underwater gliders include the following:

- Design for long-duration ocean sensing missions.
- Travel at a slow speed, which is crucial for oceanographic observations.
- Fairing shape that decreases vehicle drag, fixed wings, and a fixed tail.
- Relatively the same size, shape, and weight measuring about 2 m in length and 50 kg in weight.
- Antenna protruding from areas that does not increase vehicle drag.
- Internal mass movement to control pitch and roll.
- Ballast system that uses a hydraulic pump to move oil between the external bladder and internal reservoir similar to buoyancy-driven floats.

- Drop weight system in case of emergency.

The following discussions (Seaglider through Slocum Thermal Glider) compare the three commercial gliders in further detail.

Seaglider

The Seaglider was built, tested, and deployed by the University of Washington’s Applied Physics Laboratory (Kongsberg Maritime recently obtained the rights to produce and further develop the Seaglider). Seaglider Port Susan deployment to Possession Sound with logged GPS fixes and dead reckoning displacements (Eriksen et al., 2001).

As seen in Table 1, the speed of the vehicle is greater than or equal to 0.25 m/s in order to overcome ocean currents and cover a large ocean range. The Seaglider can travel at glide slopes from 16° to 45°. Greater glide slopes result in a shorter range, and lower glide slopes result in the longer range ideal for oceanographic surveying (University of Washington, 2013).

The Seaglider completes the saw-tooth shown in Figure 5 where a computer decides on the bearing and glide slope to the target position. The vehicle’s glide terminates at the surface with a vehicle pitch of 45° to expose the antenna located on the tail of the vehicle. The antenna contains a GPS and wireless modem to transmit and download information and new missions/directives (Eriksen et al., 2001).

The Seaglider has the ability to glide for months at a time by adjusting the volume in the buoyancy control system. Flight control is through the manipulation of the center of gravity relative to the center of buoyancy. The center of gravity and the center of buoyancy both change throughout a dive as a result of vehicle movement. The Seaglider moves the vehicle’s battery pack fore and aft to provide pitch control and rolls the battery pack left and right for roll control instead of using external control surfaces (Eriksen et al., 2001).

The buoyancy system is similar to the design seen on the buoyancy-driven

| TABLE 1 |
| Seaglider Specifications (University of Washington, 2013). |

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>52 kg</td>
</tr>
<tr>
<td>Hull diameter</td>
<td>30 cm</td>
</tr>
<tr>
<td>Vehicle length</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Wing span</td>
<td>1 m</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>1000 m</td>
</tr>
<tr>
<td>Speed</td>
<td>0.25 m/s</td>
</tr>
<tr>
<td>Range</td>
<td>4600 km</td>
</tr>
<tr>
<td>Glide angle</td>
<td>16°–45°</td>
</tr>
</tbody>
</table>

FIGURE 5
Seaglider path.
ALACE floats. The buoyancy system includes a boost pump with a pump and motor manufactured by Hydro-Leduc (Eriksen et al., 2001). The internal reservoir made of a Bellowfram Diaphragm (Eriksen et al., 2001) contains a vacuum for oil to bleed from the external to internal reservoir. Moving the oil from the internal to external reservoir is done through an axial pump mechanism (Eriksen et al., 2001).

Sensors on the Seaglider include a conductivity cell, thermistor, dissolved oxygen sensor, pressure sensor, and acoustic transducer. Two battery packs of lithium thionyl chloride D-cell batteries provide high and low voltage to the vehicle. The navigation software provides a dead reckoning position during the dive cycles and corrected with actual surface positions by the use of a Kalman filter. An acoustic transducer located on the front of the vehicle is used for locating and tracking the vehicle (Eriksen et al., 2001).

Currently, the Seaglider is sold by Kongsberg Maritime and used by a number of companies and institutions to profile the ocean (e.g., one of the most famous missions was monitoring the after-effects of the Deepwater Horizon oil spill in May 2010). Seaglider milestones include the first glider to complete a mission greater than 3,800 km and the first to complete a multiglider mission. This glider completed a mission greater than 6 months in March 2005, which consisted of up to 191 days of runtime and up to 600 dives of 1,000-m depth (University of Washington, 2013). The limiting factor on duration of the Seaglider is the battery life and the longevity of the on-board components to the exposure of seawater.

Spray Glider

The Spray Glider was developed under the Office of Naval Research (ONR) with support from Scripps Institution of Oceanography and currently sold by the Bluefin Robotics Corporation. This AUV uses battery power to pump hydraulics through the buoyancy control system to change volume and power while gliding.

According to the vehicle specifications in Table 2, the Spray Glider is designed to dive up to 1,500 m at speed of up to 25 cm/s. It uses a see-saw path shown in Figure 6, controlling the dive angle during ascent and descent by moving battery packs of lithium D-cell batteries forward and backward to change pitch and rotating battery packs to change roll. At the surface, the glider rotates 90° to utilize one of the GPS and Iridium antennas located on the wing transmit data to shore and allow operators to change the course of a mission to download new missions on the fly. The wings have a thicker airfoil shape to allow for better stiffness and protection for the enclosed antenna (Sherman et al., 2001).

Figure 7 shows the schematics aboard the Spray Glider. These include conductivity and temperature sensors located on the top of the flooded tail section, fluorometer, backscatter sensor, altimeter, and an acoustic pinger to allow for underwater tracking. The emergency system consists of a drop weight that allows the vehicle to surface in case of failure (Sherman et al., 2001).

Variables involved in the glide control algorithm include heading, roll, pitch, pressure, and altitude. Sensors measuring these variables include a compass, pressure gage, and acoustic altimeter. The control loop for pitch control is proportional with a low gain, and the heading control loop includes a proportional and integral term to account for errors. A simple navigation algorithm computes distance and heading from the GPS fix to the desired waypoint (Sherman et al., 2001).

Slocum Electric Glider

The Slocum Electric Glider was developed by Teledyne Webb Research and named after Joshua Slocum, the first person to circumnavigate the globe (Webb et al., 2001). Webb produces two types of glider, a 200 m and a 1,000 m.

The hull and fixed wings of the 1,000-m electric glider are made out of composites, whereas the 200-m hull is made out of 6061-T6 aluminum. In the 200-m version, pitch and roll are achieved by translating and rotating the main battery pack, whereas with the 1,000-m electric glider, pitch is achieved by shifting mass in/out of the nose reservoir. The battery pack is used as a vernier to trim the pitch but does not rotate to adjust the roll. The vehicle does not roll much, aside from its response to yaw adjustments. The yaw moment is achieved by using a rudder on the tail and mounting the wings aft of the center of buoyancy. The antenna is located on the tail of the vehicle for communication when surfaced (Webb et al., 2001).

| TABLE 2 |
| Spray Glider Specifications (Scripps Institution of Oceanography, 2013). |
| Weight | 51.8 kg |
| Hull diameter | 0.2 m |
| Vehicle length | 2.0 m |
| Wing span | 1.1 m |
| Maximum depth | 1500 m |
| Speed | 0.25–0.30 m/s |
| Range | 4700–3500 km |
| Glide angle | 19°–25° |
The vehicle is powered by alkaline batteries, deploying from up to 30 days at a 600- to 1,500-km range as shown under the electric glider portion of Table 3. Sensors on board include GPS, compass, altimeter, RF modem, optical sensor, conductivity temperature depth (CTD) sensor, and an oxygen sensor (Webb Research Corporation, 2010). The Slocum electric glider has a buoyancy engine consisting of a single stroke pump that pushes water in and out of the nose of the vehicle. An air pump is used to inflate the air bladder using air that is in the interior of the hull. This provides additional needed buoyancy when the vehicle is on the surface of the water (Webb Research Corporation, 2010).

**Slocum Thermal Glider**

The Slocum thermal glider, similar to the electric glider as shown in Table 3, uses the environmental thermal energy to propel the vehicle vertically in the water. Also developed by Teledyne Webb Research, this glider’s engine uses the melting and freezing of wax to harvest energy from the ocean and drive the buoyancy system. The thermal glider moves oil into a flexible bladder in the nose cone for pitch control. Figure 8 displays an image of the

**TABLE 3**

Slocum Glider Specifications (Webb Research Corporation, 2010).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>51.8 kg</td>
</tr>
<tr>
<td>Hull diameter</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Vehicle length</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Wing span</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>1500 m</td>
</tr>
<tr>
<td>Speed</td>
<td>0.25–0.30 m/s</td>
</tr>
<tr>
<td>Range</td>
<td>4700–3500 km</td>
</tr>
<tr>
<td>Glide angle</td>
<td>19°–25°</td>
</tr>
</tbody>
</table>
Slocum thermal glider that reveals features common to both electric and thermal gliders. The main difference is the thermal engine tubes located underneath the vehicle protruding past the antenna fin.

The feasibility of the thermal glider includes a long projected endurance of up to 5 years and the ability to operate in 65% of the world’s oceans and dives down to a maximum depth of 1,200 m. The disadvantage of this thermal engine is that it can only be used when a thermal gradient is available (Webb et al., 2001).

ACSA SeaExplorer

The SeaExplorer is similar to the other electric gliders except that it does not have wings or external moving parts aiding launch and recovery operations while reducing the risk of entanglement. Its modular design includes an independent payload section located at the front of the vehicle that can be changed rapidly between missions. Sensors include a pumped CTD, oxygen optode, turbidity, chlorophyll, backscatter CDOM, hydrocarbon fluorescence, and an acoustic detector and recorder. (ACSA SeaExplorer, 2013).

Military Gliders

The military has also developed an advanced underwater winged glider based on the air force’s Flying Wing design, the Liberdade XRay (Figure 9). This vehicle is “being developed as a part of the Navy’s Persistent Littoral Undersea Surveillance Network system of semiautonomous controlled mobile assets. Persistent littoral undersea surveillance network uses unmanned underwater vehicles and AUVs to monitor shallow-water environments from fixed positions on the ocean floor or by moving through the water to scan large areas for extended periods of time (D’Spain et al., 2007).

The XRay was developed primarily with the aid of the Marine Physical Laboratory at Scripps Institution of Oceanography and the University of Washington’s Applied Physics Laboratory, and also with the following institutions, universities, and corporations: University of Texas at Austin’s Applied Research Laboratory; applied research laboratory at Penn State University; Massachusetts Institute of Technology; Woods Hole Oceanographic Institute; Harvard University; Scientific Applications International Corporation; Bluefin Robotics; Metron; Heat, Light, and Sound Research; and the Space and Naval Warfare Systems Center in San Diego.

The vehicle is the largest of all underwater gliders having a 6.1-m wing span, which is an advantage in terms of hydrodynamic efficiency and space for energy storage and payload. The glider’s primary function is to track quiet diesel-electric and fuel cell submarines operating in shallow water. According to military doctrine, it can “be deployed quickly and covertly, and then stay in operation for a matter of months. It can be programmed to monitor large areas of the ocean (maximum ranges exceeding 1000 km with on-board energy supplies). The glider is very quiet, making it hard to detect using passive acoustic sensing” (D’Spain et al., 2007).

The vehicle was designed for easy and rapid deployment and retrieval as well as payload carrying capability, cross-country speed, and horizontal point-to-point transport efficiency. Liberdade XRay’s first major ocean test was performed in August 2006 in Monterey Bay, California, where it reported real time via a 3.0- to 8.5-kHz underwater acoustic modem as well as with an Iridium satellite system while on the surface. The vehicle had an array of 10-kHz bandwidth hydrophones located in the SONAR dome and across the leading edge of the wing. The XRay exceeded a 10:1 glide slope ratio (ONR, 2008). Later deployments were in the Philippine Sea, near Hawai, and in Monterey Bay using the hydrophone array “to detect low frequency source signals, marine mammals (blue and humpback whales), and ambient ocean noise” (Autonomous Undersea Vehicle Applications Center, 2013). The XRay glider is hoped to achieve 1- to 3-knot cruise speeds, have a 1,200- to 1,500-km range, and be able to remain on-station up to 6 months in partial buoyant glides.

Another glider developed for ONR is the Exocetus [x-o-seat-us] Coastal Glider. Eighteen gliders that were delivered to the U.S. Navy have a combined operating time of 4,500 h. These gliders were designed to operate in coastal waters where high currents and densities changes occur from fresh water entering coastal waters. The Slocum, Seaglider, and Spray Gliders are designed for open-ocean operations and do not have the capability of operating in coastal waters. The Exocetus Coastal Glider is designed to easily add more sensors without any or minimal changes to the glider housing (Exocetus, 2013).
**Research Gliders**

One of the first gliders is the ALBAC, which conducted sea trials at the Suruga Bay of Japan in 1992. The vehicle (Figures 10 and 11), developed at the University of Tokyo in the laboratory of Tamaki Ura, does not have an active buoyancy control system but has a simple drop weight system with only one glide cycle.

The ALBAC has fixed wings and a vertical and horizontal tail. It is 1.4-m long and 120-cm wide, weighs 45 kg, and can dive to depths of 300 m at speeds of 1–2 knots (0.5–1.0 m/s). It has horizontal tail fins that change angle at inflection from downwards to upwards gliding, a feature not present in other gliders. The wings and tail are larger in comparison to the body than on the Slocum, Spray, or Seaglider. ALBAC moves a battery pack internally to control pitch and yaw in the same manner as Seaglider. Because it has no ballast pump, ALBAC carries batteries to power only its instruments and actuators.

ALBAC carries flight sensors including compass, depth, pitch, roll, and a propeller-type velocity meter. Note that Slocum, Spray, and Seaglider do not carry velocity meters in order to conserve power and because of the difficulty of accurately sensing velocity at glider operating speeds (Kawaguchi et al., 1993).

The ALBAC vehicle glides horizontally by up to 20° down from the horizontal plane and controls its trajectory by changing pitch angle and roll angle by displacing the center of gravity. To accomplish this, an internal actuator system changes the location of the center of gravity longitudinally and laterally by moving a weight. The vehicle has no external communication ability. It has a 3-L dry payload space for scientific measurement devices, which consists of a 0.5 ellipse-shaped front cap; a cylindrical pressure hull; a corn-shaped tail cap with a vertical stabilizing fin; a pair of wings; tail wings; and various electronic devices, that is, a depth sensor, a gravity sensor, a magnetic sensor, two CPUs, interface boards, and two actuators to trim and roll. A ranging sensor, a velocity sensor, a drop ballast system, a tail angle trigger, and a transponder are fitted in the front and tail caps (Alvarez et al., 2009).

A few research institutes have been experimenting with glider design. Florida Institute of Technology (Florida Tech) has been developing a research glider (Figure 12) that introduces a set of external control surfaces on the wings, also known as flaps. These external surfaces move up and down to aid in the pitch, roll, and horizontal movement control of the glider. The bendable live hinge on this glider is made out of a thin, flexible, low-modulus fiberglass. The glider has a system of external wing control surfaces for steering and a mechanical buoyancy engine. The vehicle is a fully functional underwater glider with a unique open interface buoyancy engine with the Raspberry Pi (http://www.raspberrypi.org/) as the controlling computer. The glider is designed for oceanographic education in shallow water and is a platform for artificial intelligence and navigation algorithm research. The vehicle is in very low cost (under $5,000) and small in size (i.e., deployable from a small boat). The current commercial gliders have an estimated construction cost ranging from $25,000 to $60,000 without instrumentation and a refueling cost ranging from $800 to over $10,000 depending on the battery type (Davis et al., 2003).

**Hybrid Vehicles**

Hybrid designs are being developed by a couple of research institutions. For example, at the University of Pisa, Italy, the ISME laboratory has been...
involved in the development of the “Folaga” hybrid vehicle (Caffaz et al., 2010) (Figure 13). The Folaga buoyancy and pitch control is similar to that of the three commercial gliders but uses jet pumps and screw propellers for yaw and surge motion. The vehicle is targeted for shallow/coastal water applications and is very maneuverable. The vehicle can remain stationary in either a hover position, lie on the ocean floor, or dive vertically along the depth axis.

Another hybrid under development at Florida Tech will travel under power or in glide mode (Figure 14). This vehicle is being designed to obtain water samples, make photographic/video images of specimens in the water column, and specify the environmental characteristics of the data field. Furthermore, it is expected to possess a wide array of traditional oceanographic instruments that can be used by the vehicle’s control system to make mission/navigational changes. The vehicle’s ability to obtain specimen/water samples and photographs directly affects the design of the vehicle more than the addition of oceanographic instruments. Water samples are to be collected using a series of small automatically closing specimen bottles, and two digital cameras are used to document what is floating through the water column.

Florida Tech’s powered glider design characteristics are mission applications to 6,000-m ocean depths, modular design with interchangeable scientific modules, quick assembly and disassembly of components, easy battery access for replacement and recharging during missions, greater scientific and instrument payload space, and ability to land. Unlike torpedo-shaped gliders, the structure of the Florida Tech’s powered glider has a rectangular frame that is approximately 1.5 × 2 m². The vehicle is designed for easy assembly and disassembly with easy access to the two 17 inches in diameter and 3/8-inch-thick vehicle control system and scientific pressure housings.

A third hybrid glider is the Sterne Glider being developed at Ecole Nationale Superieure D’Ingenieurs in Brest, France. This hybrid glider has both a glide (buoyancy) and a thruster mode. The 4.5-m-long, 0.6 m in diameter, and 900 kg in mass vehicle has buoyancy control and a thruster for forward propulsion and is capable of gliding at 1.3 m/s.

The Sterne is designed to conduct surveys by gliding or by flying level using its thruster, which, when powered, has the range of an estimated 200 km with an estimated speed of 3.5 knots (1.8 m/s). The vehicle can go 2.5 knots (1.3 m/s) when gliding. It has two fixed wings, two actuated horizontal tail fins, and a vertical tail with rudder and moves a battery pack to control pitch (Graver, 2005).

The Wave Glider® (Figures 15 and 16) by Liquid Robotics is a surface vehicle that has a component that resides underwater; thus, it is included in this article for completeness. The concept uses ocean waves as its primary energy source for propulsion. During the spring and summer of 2008, the Wave Glider underwent extensive field testing in the Pacific Ocean and, since then, has performed superbly in numerous ocean surface studies throughout the world.

The vehicle consists of a surface float (similar to a surfboard) that is tethered to a subsurface glider about 6 m below the surface. This subsurface glider has six sets of wings (Figure 17) with a mechanism that “ratchets” in such a way that, when a wave at the surface lifts the float, the entire system (float and glider) rises and the wings propel the vehicle forward. As the wave passes by, the glider sinks and the wings pivot to create a downward pitch causing the glider to fly forward and slide downward at an angle. Because the float and glider are tethered together, the glider will stop at the end of the line’s reach causing the surface float to move forward. Consequently, the whole subsurface system moves forward in a “sawtooth” pattern.
corresponding to the waves. The surface float shoots forward in small bursts across the water controlled by a rudder. The vehicle requires at least 7 m of water and a minimum wave height to operate. It has high endurance and is able to station-keep, and the method of movement allows it to move in any direction regardless of wave direction. The vehicle does not “surf” the wave but, rather, traverses up a wave. All it needs is the up-and-down motion that translates into forward motion of the vehicle. The vehicle moves quite slowly, and high currents are a problem.

The Wave Glider has a total mass of 90 kg. The underwater sub (40 × 191 cm) is attached to the surface float (208 × 60 cm) via a 6-m tether. Wave Gliders have survived hurricanes and extended periods at sea with waves over 6-m high and winds over 26 m/s. The vehicle can carry an array of sensors and on-board data collection tools, satellite telemetry, optical water quality sensors (e.g., to detect oil, chlorophyll, or CDOM), on-board weather station, solar charging panels with a 665 Wh rechargeable lithium-ion batteries. The data are streamed via the Iridium satellite network. The Wave Gliders can be programmed for autonomous operation or directly controlled by a remote pilot over the Internet. Continuous, nearly real-time (every 2 min) communication is provided either by the Iridium satellite network or by cellular phone or radio links, which can be used for piloting or data transmission (Coxworth, 2011).

The Wave Glider’s surface float houses the electronics along with solar cells to recharge the electronic battery packs. The most significant problem with the vehicle is its recovery. To date, the designers have failed to implement a retractable system for the subsurface wings, making it difficult to retrieve. In 2012, Florida Tech students showed that a retractable system for the wings is feasible (Figure 18).

Sensors

Gliders are currently using a wide range of scientific instrumentation,
but this instrumentation is limited due to vehicle size. As glider types increase in variation, size, and complexity, accommodations for collecting specimens and integration of large sensor packages will occur. The Slocum, Spray, and Seaglider are too small for specimen collecting or other larger instruments. Additionally, the sawtooth glide pattern is not optimal for certain types of data collection such as sidescan sonar. Only larger hybrid vehicles can make full use of all instrument types. Unfortunately, this forces the need of larger vessels and more manpower to deploy and recover these vehicles.

Some of the instruments used on AUVs that can/could be used on autonomous underwater gliders that are rated down to 6,000 m are Sidescan sonar, Falmouth Scientific NXIC CTD (a fully integrated instrument platform that is compact, robust, and equipped with fully integrated conductivity, temperature, and depth sensors) (http://www.falmouth.com/), Chelsea AQUAtracka III (a compact, lightweight, submersible fluorimeter for the detection of chlorophyll-a, dye tracing, or turbidity that, when connected to the CTD Sensor, provides measured values of chlorophyll, rhodamine, amido rhodamine, and fluorescein), UV-VIS Spectrometer, video cameras (provide high-resolution video or photo data that can be stored via a frame grabber to the integrated hard disk), and acoustic hydrophones.

Future

As autonomous vehicles are developed to take on more responsibilities, program algorithms will be developed to accommodate these tasks. Currently, new distributed on-board collaborative autonomous vehicle control programs are being developed that will enable an individual vehicle to coordinate and control multiple vehicles. This technique enables “collaborative” capabilities among multiple vehicles. With on-board collaborative control, the vehicles operate as a group, functioning together. The vehicles process and communicate relevant information allowing individual vehicles and the entire school of vehicles to change their mission, autonomously, in response to sensor inputs. The concept of working and acting collaboratively is very useful for science in sampling entire regions for a specific organism, substance, or phenomenon. The control of an AUV, whether powered or a glider, will also utilize some combination of traditional, artificial intelligence and neural network navigation that uses Kalman filters.

One of the requirements for a long-duration AUV, whether powered or a glider, is the need for a robust, fault tolerant navigation system. In addition to the robustness issue, there are core issues of nonlinear control as they pertain to maneuverability and sea keeping. In both issues, neural networks offer very promising solutions. For example, the calculation of the distances and the relative velocities will use positioning data as well as measuring inertial sensor data. In order to increase the reliability of the data, a reconciliation of both processes must be accomplished accurately and efficiently. The coordination of the target trajectories of AUVs can yield vital information for positioning prognosis.

Commercial powered AUV systems use a combination of internal inertial, compass, and accelerometer sensors, in conjunction with external active acoustic triangulation methods (long baseline, short baseline, ultrashort baseline). These have met with some success for applications of cable following, standard grid surveying, search and rescue, and signal following. But in each of these cases, the system is unable to respond to (a) abrupt changes in external environment, (b) system damage, and (c) uncertain or indeterminate data input. In these areas, some scattered research on the use of neural networks has been performed with success, addressing specifically the fault tolerance, docking, and ranging issues. For example, Wilson (Douglas, 2008) successfully evaluated the use of a neural network for a spaceship application providing robust navigation despite thruster failure. Most of the work in this area has been in spacecraft, but the work is directly applicable to underwater and surface vehicles. In most of the cases, a back-propagating network is applied using position, rotation, or acceleration error as the training tool. In each case, changes to the vessel control system itself or in the external environment (displacement forces) cause the system to update its training, which in turn prompts it to compensate for the change in forces. Ship navigation has been evaluated using neural network-based adaptive critic designs. For AUV control, a neural network has been modeled at the University of Hawaii for the problem of depth gradient descent only. In each case, the results were very positive, indicating that, if generalized, a full neural network system could provide robust navigation for an AUV.

In addition to the constituent issues above, powered and glider AUVs are beginning to address the search for environmental pollutants; identify and analyze biological systems; locate and identify artificial acoustic sources; scan long term for physical, biological, or chemical phenomena of interest; and further develop noninertial navigation.
These vehicles will also soon process multisensory data from the pattern recognition and data classification modules to provide control inputs for the navigation system. Thus, the system will be able to track and monitor multiple targets and integrate sensor inputs from a variety of sources into multisensory patterns, that is, acoustic with salinity, temperature and pressure, spectrographic with temperature, and so forth. Instead of traditional analytical methods where the individual data sets are correlated one by one, the system will be able to search for patterns in all sets together.

Conclusion

AUVs are robust commercial vehicles being used by industry, governments, military organizations, and communities throughout the world. The glider is the latest of these vehicles, which is becoming widespread for oceanographers and other personnel needing oceanographic data for their work. As stated by David Smeed of the National Oceanography Centre, Southampton, England, “gliders are one of the technological developments that are changing the way we observe the ocean, and it is very exciting for us to be at the forefront of their application in ocean and climate science” (Liquid Robotics, 2013).

Authors:
Stephen Wood
Florida Institute of Technology
150 W. University Boulevard
Melbourne, FL 32901
Email: swood@fit.edu
Cheryl E. Mierzwa
Bluefin Robotics
553 South Street, Quincy, MA 02169
Email: cherylmierzwa@gmail.com

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