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Autonomous Underwater Gliders

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1. Introduction

Over the past few decades, a range of strategies and techniques has been used to monitor the sea. More recently, the role of monitoring has been expanded to include the use of autonomous underwater vehicles to perform ocean surveys. With these vehicles it is now possible for the scientist to make complex studies on topics such as the effect of metals, pesticides and nutrients on fish abundance, reproductive success and ability to feed, or on contaminants such as chemicals or biological toxins that are transported in particulate form and become incorporated into living organisms (plankton, bivalves, fishes) or become deposited in bottom sediments. The scientist or environmentalist may desire to detect hazardous substances in the ocean such as chemicals from an underwater vent or toxic algae such as red tide. Additionally, the military's detection of mines, biological, chemical or radioactive threats are also very important in the monitoring of the seas.

These considerations explain today's development of new types of autonomous underwater vehicles with integrated sampling equipment that is able to perform a wide-range of fully automated monitoring surveys over extended periods of time. These vehicles survey and monitor the sea environment in a cost-effective manner combining survey capabilities, simultaneous water sampling and environmental data gathering capacities. Included in these types are autonomous underwater gliders that have the ability to glide for long distances and are in some cases able to travel under power. 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.

Gliders are 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, which require greater control over the vehicle (the free-drifting profiling Argos floats that scientists often use have no control capabilities beyond descending and rising vertically in the water column. The newest Argos float model cycles to 2000m depth every 10 days, with 4-5 year lifetimes for individual instruments)(Argos, 2008). 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 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, pollution of ocean waters can be detected and quantified in an automated way; 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. Depending on the vehicle's configuration the scientist may have the ability to take fly-by photographs of organisms in the water column.

Initially gliders were targeted for missions that were a combination of three archetypes: time series, transects and roving assistants to research cruises (Sherman et al., 2001) by the scientist for surveying and monitoring the deep-sea environment. This is still true but scientists at various institutions such as Florida Institute of Technology's Department of Marine and Environmental Systems in Melbourne Florida have desired more. A survey was conducted of the opinions of marine scientists (biological, physical, chemical oceanography, marine biology, environmental science, and ocean engineers) and the biological research published on the Internet with respect to which organisms take precedence in ocean studies was analyzed. From these investigations, one of the most important biological groups in the life cycle of higher ocean organisms (e.g., fish), and consequently a very important element in the research of all marine organisms, was found to be the phytoplankton[1]. Phytoplankton play a fundamental role in the ocean's biological productivity and directly impact the climate. It is important that scientists determine how much phytoplankton the oceans contain, where they are located, how their distribution is changing with time, how much photosynthesis they perform, and what organisms such as marine invertebrate larvae feed upon the phytoplankton (Herring, 2007b).

Next, the marine invertebrate larvae and zooplankton (e.g. krill - *Euphausia superba*) were found to be a very important biological group that affect the life cycle of higher ocean organisms. Krill are small shrimp like crustaceans that are the most important zooplankton species associated with sea ice and are very important in the Antarctic food web. Krill occur in groups or large swarms and occupy a niche similar to that of the herring in the North Atlantic. Krill attain a size of 6-cm and feed primarily on phytoplankton or sea ice algae. Its feeding apparatus is built to filter phytoplankton out of the water column and to scrape algae from the ice. Krill is the staple food of many fish, birds and mammals in the Southern Ocean. The biomass of Antarctic krill is considered to be larger than that of the earth's human population and krill swarms can occupy an area equivalent to 2.5 times the size of Washington, DC (AWI, 2008a).

Southern Ocean GLOBEC is conducting a study of the Antarctic krill in which they are attempting to define the habitat, prey, predators, and competitors of this species. This organization could make immediate use of such a vehicle as the autonomous underwater glider. In fact, recent evidence indicates that seasonal coverage is necessary to fully understand the linkages between the environment, krill, and top predators.

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[1] Phytoplankton are microscopic plants that live in the ocean. There are many species of phytoplankton that grow abundantly in oceans around the world and are the foundation of the marine food chain. Since phytoplankton depend upon certain conditions for growth, they are a good indicator of change in their environment making them of primary interest to oceanographers and environmental scientists (Herring, 2007a).

The zooplankton science questions that a glider could help answer are (AWI, 2007b):

1. What is the abundance of krill?
2. How many populations are there?
3. How do krill survive during winter with a minimal food supply?

A third important biological group that affects the life cycle of higher ocean organisms is the algae, which at times is responsible for harmful algal blooms (HAB). HABs occur throughout the world, affecting European and Asian fisheries, Caribbean and South Pacific reef fishes, and shell fishing along the coasts of the United States. These HABs are caused by several species of marine phytoplankton, microscopic plant like cells that produce potent chemical toxins (Mote, 2007).

Research on these and other biological groups requires non-traditional approaches to acquire the needed scientific information. Various institutions are addressing this issue by developing vehicles which implement special biological catching and photographing systems to document small visible species, using a navigation system that will use the scientific data to control the vehicle's movement.

In addition to biological investigations, documenting the chemical make-up of all areas surveyed, specifically where samples were taken is important for the scientist to obtain a complete understanding of that region. The chemical layout and the corresponding biological data are normally for a specific transect, but a vehicle's transect might not be on a traditional grid pattern. For example, the scientist may desire to obtain samples within a polluted area with a specific concentration of the pollution. To accomplish this, non-traditional approaches of navigation are required to acquire the desired scientific information. Data from geophysical and acoustic sensors can be combined, analyzed and entered into the navigation system to aid in controlling the vehicle with respect to the chemical information supplied.

To date, most survey AUVs have relied on rudimentary single variable differential gradient navigation systems, external triangulation, or inertial based dead reckoning systems. Research is now being conducted using the changes in various geophysical parameters as navigation cues (i.e., phenomenon based navigation). Some of these parameters are temperature, salinity, turbidity, chlorophyll, rhodamine, fluorescein, and passive acoustic signals. These navigation techniques are expected to provide a better understanding of the geophysical environment where biological samples are obtained, in addition to characterizing the data.

2. Vehicles

Looking at the current situation in AUV technology (see Figure 1), there are currently over 50 different types of AUVs in research and commercial operation, just a few of these systems are: Hydroid's REMUS (USA), Bluefin Robotics Corporation's Odyssey (USA), Woods Hole's ABE (USA), FAU's (USA), Boeing's, Oceaneering's and Fugro's Echo Ranger (USA), Kongsberg Simrad's Hugin 3000 (Norway), Sias-Patterson's Fetch (USA), University of Southampton's AUTOSUB (England), Alive and Swimmer (France), and Hafmynd's Gavia (Iceland). Of these autonomous underwater vehicles all but a few of them are 100 percent powered. Three of these vehicles are torpedo shaped (see Figure 2) and move without power. These are the Webb Research Corporation's Slocum glider (the name Slocum commemorated the first person who sailed around the world solo, Joshua Slocum), University of Washington's Applied Research Laboratory's "Seaglider", and Scripps Institution of Oceanography "Spray" (Spray was the name of Joshua Slocum's boat when he sailed around the world) currently sold by Bluefin

Robotics Corporation. These three vehicles are from the United States of America and have the ability to do studies in glide mode.

These vehicles glide slowly down to a specified depth and then back to the surface using a buoyancy control system tracing a saw-tooth profile, observing data such as temperature and conductivity versus depth. When the vehicle is at the surface, positioning is obtained via GPS and communication between the vehicle and the home base is via satellite. The three gliders are small semi-torpedo shaped AUVs that control their forward motion by the glide path taken and changing buoyancy. Wings allow steerable gliding, thus horizontal propulsion.

Fig. 1. 1) Woods Hole Oceanographic Institution, USA: Autonomous Benthic Explorer (ABE), 2) ECA, France: ALISTAR 3000, 3) Boeing, Oceaneering and Fugro, USA: ECHO RANGER, 4) Bluefin Robotics, USA: BLUEFIN 21, 5) Southampton Oceanography Center, Great Britain: AUTOSUB, 6) Florida Institute of Technology, USA: TUVAAQ, 7) Kongsberg-Simrad, Norway: HUGIN 3000, 8) Atlas Maridan, Germany: M600, 9) Hydroid, USA: REMUS, 10) Cybernetix, France: ALIVE, 11) Cybernetix, France: SWIMMER, 12) Autonomous Undersea Systems Institute, USA: SAUV.

The Slocum glider, the Seaglider and Bluefin's glider Spray 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 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 saw-tooth path as the vehicle descends or ascends.
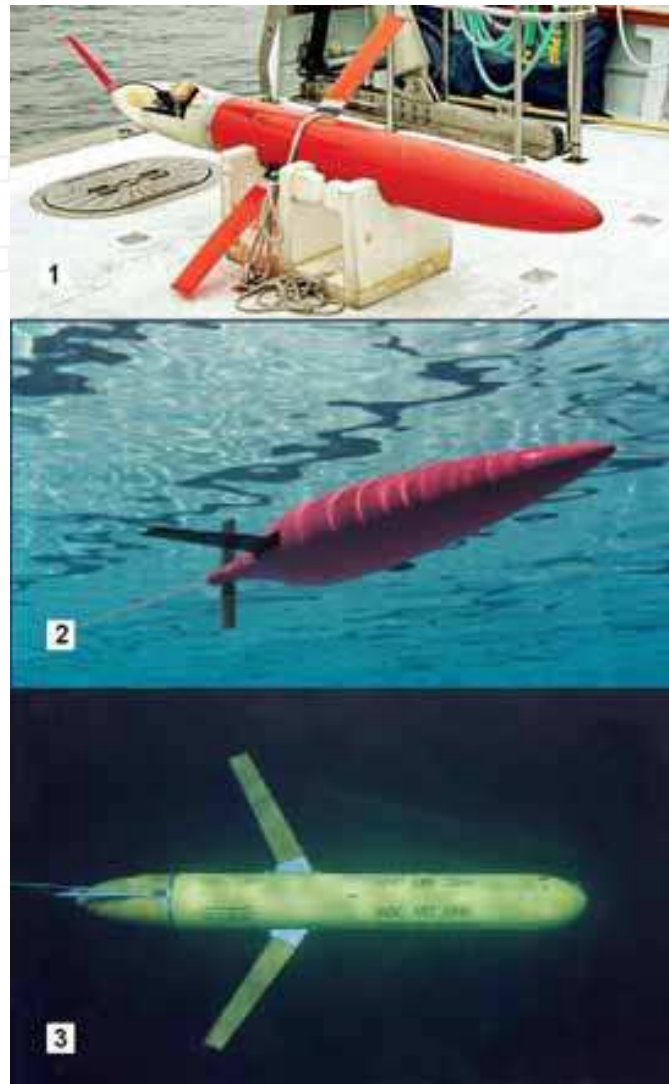

Fig. 2. 1) Spray, 2) Seaglider, 3) Slocum Glider (Photos courtesy of Bluefin, Applied Physics Laboratory, University of Washington and Webb Research Corporation)

These three 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. Consequently, this requires a design that has minimal space for instrumentation and is limited in its function/ capabilities. These vehicles are relatively inexpensive, typically less than the cheapest powered AUV's (e.g., $100,000 for the EcoMapper AUV by YSI Inc.), costing less than a week and a half of ship time for a research vessel.

With respect to these gliders four basic sampling modes exist: 1) vertical sampling where the forward motion of the vehicle counters any local currents to maintain position, 2) horizontal saw-tooth 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 repeat sampling over an extended duration.

Spray and Slocum Battery/Electric Gliders

The Slocum Battery (Webb *et al.*, 2001) and Spray Gliders (Sherman *et al.*, 2001) have been optimized for missions in shallow coastal environments. Each of these vehicles uses battery power to control the buoyancy.

The Slocum Battery is controlled by different methods. The pitch and roll is controlled by translating and rotating the internal battery packs. A rudder controls the turning rate and the pitch moment and the buoyancy at the surface are aided by the inflation of an airbladder. The Slocum battery uses an efficient shallow water single stroke pump to move water in and out of the vehicle for volume control. The communication and GPS antennas are embedded in a vertical stabilizer, which rises above the ocean surface when the vehicle is pitched forward (Griffiths, 2002). Additionally, "the yaw moment for steering is achieved by mounting the wings aft of the center of buoyancy, and when rolled, the lateral component of lift creates a yaw moment" (Webb *et al.*, 2001).

Slocum Battery/Electric Specifications (Webbresearch, 2008a)(Griffiths, 2002)

- Weight: 52 kg
- Hull Diameter: 21.3 cm
- Vehicle Length: 1.5 m
- Wing Span: 120 cm
- Depth Range: 4 – 200 m (coastal model or 1000 m (1 km model)
- Payload: 3 to 4 kg
- Speed: 0.3 to 0.4 m / sec
- Energy: alkaline batteries
- Range: 1500 km
- Navigation: GPS, internal dead reckoning, altimeter
- Sensor Package: conductivity, temperature, depth
- Communications: RF modem, Iridium satellite, ARGOS, Telesonar modem

Spray (Spray, 2008a)

- Weight: 51 kg
- Hull Diameter: 20 cm
- Vehicle Length: 2 m
- Wing Span: 110 cm
- Depth Range: 200 – 1500 m
- Payload: 3.5 to 51.8 kg depending on the glide ratio between 19 and 25 degrees
- Speed: 0.25 – 0.35 m/ sec horizontal
- Energy: Primary lithium sulfuryl chloride batteries
- Range: 3500 to 4700 km depending on the glide ratio.
- Navigation: GPS, and internal dead reckoning, altimeter
- Sensor Package: Sensors used include: Precision Measurement Engineering CTD; modified Sea Bird 41 CP CTD with seawater pump; Sea Point Optical Backscatter Sensor; Sea Point Chlorophyll Fluorometer; Tritech PA200 acoustic altimeter for bottom avoidance; and Sontek Argonaut-SGP 750-kHz Acoustic Doppler Current Profiler.
- Communication: Iridium satellite

The Spray glider (see Figures 3 and 4) is similar to the Slocum Battery Glider but with a more hydrodynamic shape giving it about fifty percent less drag than the Slocum Battery (Sherman et al., 2001). The Spray was targeted for long-range up to 4700 km and down to 1500 meters depth by optimizing the use of energy. Use of a high-pressure reciprocating pump with external bladders makes the vehicle similar to the ALACE floats (Davis et al., 1992).
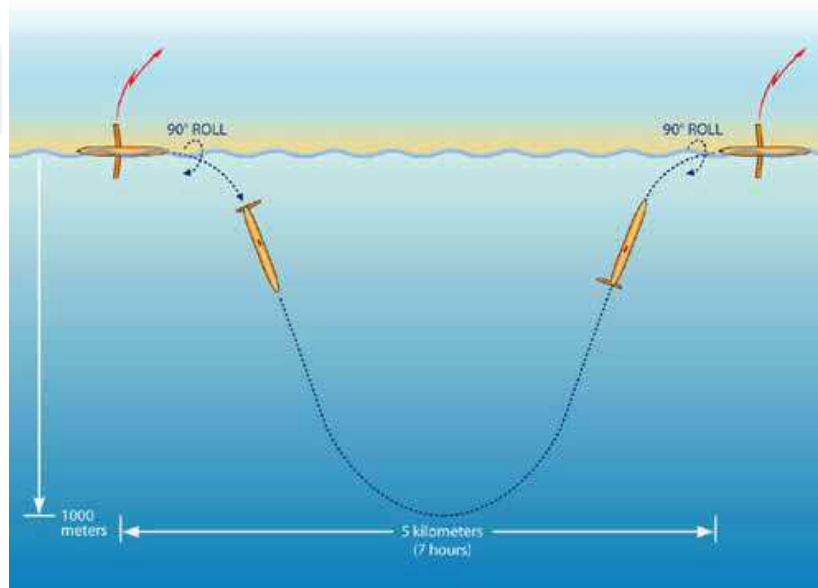

Fig. 3. Spray's method of travel (Spray, 2008b)

The "glide control in Spray is achieved exclusively by axial translation and rotation of internal battery packs. Pitch is controlled simply by moving the center of gravity in the manner of a hang glider. Turning is initiated by rolling. This gives the lift vector a horizontal component and induces vehicle sideslip in the plane of the wing in the direction of the buoyant force. The horizontal component of lift provides the centripetal force for turning while sideslip acting on the vertical stabilizer produces the yaw moment needed to change vehicle heading. For example, to turn right during descent the right wing is dropped, like a conventional airplane, generating a lift component to the right that drives the vehicle to the right. Sideslips down and to the right acts on the vertical stabilizer causing the nose to yaw to the right. To turn right in ascent the glider is rolled oppositely by dropping the left wing" (Griffiths, 2002).

Additionally, the vehicle must rotate 90 degrees to present the GPS and satellite communication antennas housed in a wing. Payload is mounted either in the expandable aft flooded component section or on the hull.

Seaglider & Deepglider

The Seaglider and Deepglider (see Figures 5, 6 and 7), commercially sold by iRobot (Bedford MA, USA), are similar to the Spray and Slocum Battery gliders. The Seaglider and Deepglider are identical in looks but the Deepglider is made out of a composite pressure hull of thermoset resin and carbon fiber making it capable of diving to a depth of 6000 meters (Osse & Lee, 2007)(Osse et al., 2007). The Seaglider using an efficient use of energy allows it to operate one-year 4600 km missions (Eriksen *et al.*, 2001). Seaglider uses a hydrodynamic aluminum pressure hull that is contained within a free-flooded fiberglass

fairing[2] that supports the wings. The flooded aft section is used to carry self-contained instruments on both the Seaglider and Deepglider. Both vehicles have a trailing antenna rod and the fairing encloses the pressure hull. In weak currents the vehicles can maintain position by pitching vertically with minimal buoyancy. As with the Slocum series and Spray gliders, the Seaglider and Deepglider control their buoyancy with a hydraulic system similar to the ALACE system. In both the Seaglider and Deepglider it is the movements of internal masses (i.e., batteries) which control the pitch and yaw of the vehicle while gliding, and also raise the antenna for communication and GPS navigation. Another interesting aspect of these two vehicles is that due to the lifting wings being so far aft the turning method is opposite to what one would expect (i.e., opposite to the Slocum and Spray gliders). To turn right while descending the left wing is lowered so that the wing lift pushes the stern left, "overcoming lift off the vertical stabilizer, and initiating a turn to the right. Hydrodynamic lift on the side slipping hull produces the centripetal force to curve the course. Conversely, in ascent a roll to the left produces a left turn" (Griffiths, 2002).

The Seaglider has made thousands of dives since its inception in 1999. Some of these dives can be seen on Seaglider's website: http://www.apl.washington.edu/projects/seaglider/summary.html. The first Deepglider tests were made in November 2006 off the Washington state coast where it made test dives for 39 days with dives down to 2713 meters depth and a lateral distance of 220 km.

Seaglider (Griffiths, 2002)(APL, 2008) (Osse et al., 2007)

- Weight: 52 kg
- Hull Diameter: 30 cm
- Vehicle Length: 1.8 m
- Wing Span: 1 m
- Depth Range: 1000 m
- Payload: 25 kg
- Speed, projected: 0.25 m/ sec (1/ 2 knot) horizontal
- Energy: Lithium primary batteries
- Energy: Lithium primary batteries
- Range: 4600 km (3800 km proven mission)
- Navigation: GPS, and internal dead reckoning, altimeter
- Sensor Package: Sea-Bird temperature-conductivity-dissolved oxygen,
                                        Wet Labs fluorometer-optical backscatter
- Communication: Iridium satellite

Deepglider (Osse et al., 2007)

- Weight: 62 kg
- Hull Diameter: 30 cm
- Vehicle Length: 1.8 m
- Wing Span: 1 m
- Depth Range: 6000 m
- Payload: 25 kg
- Speed, projected: 0.25 m/ sec (1/ 2 knot) horizontal
- Energy: Lithium sulfuryl chloride batteries

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[2] A **fairing** is a structure whose primary function is to produce a smooth outline and reduce drag

- Range: 8500 km
- Navigation: GPS, and internal dead reckoning, altimeter
- Sensor Package: Sea-Bird temperature-conductivity-dissolved oxygen,
                                Wet Labs fluorometer-optical backscatter
- Communication: Iridium satellite
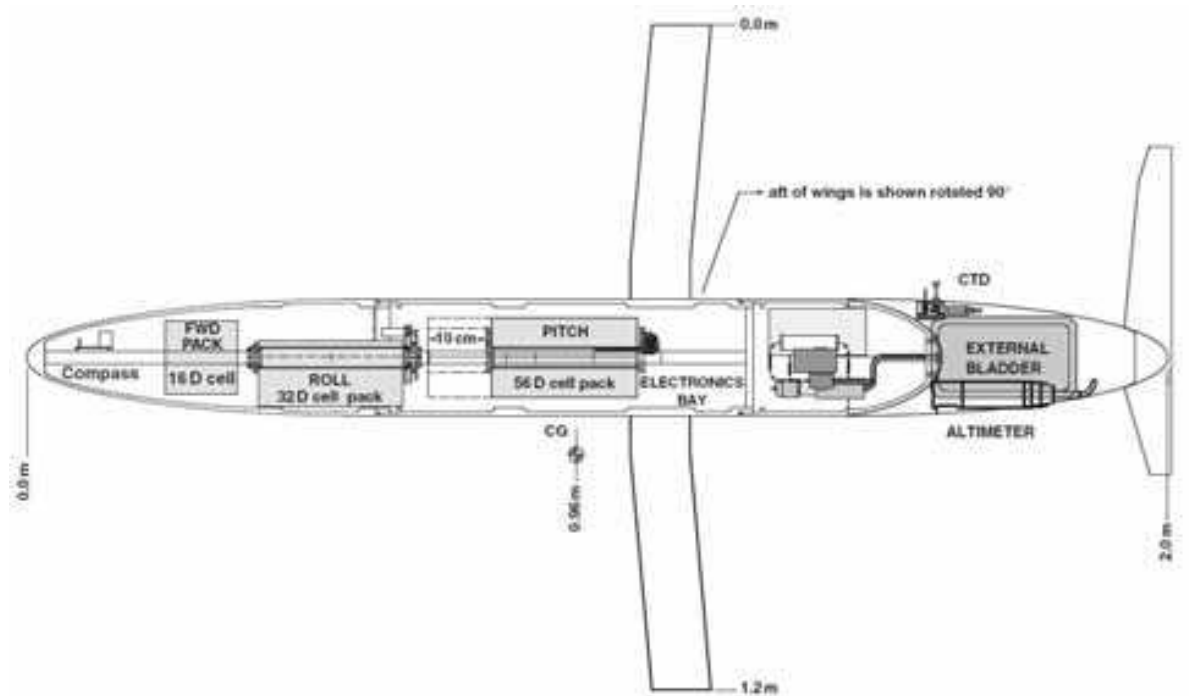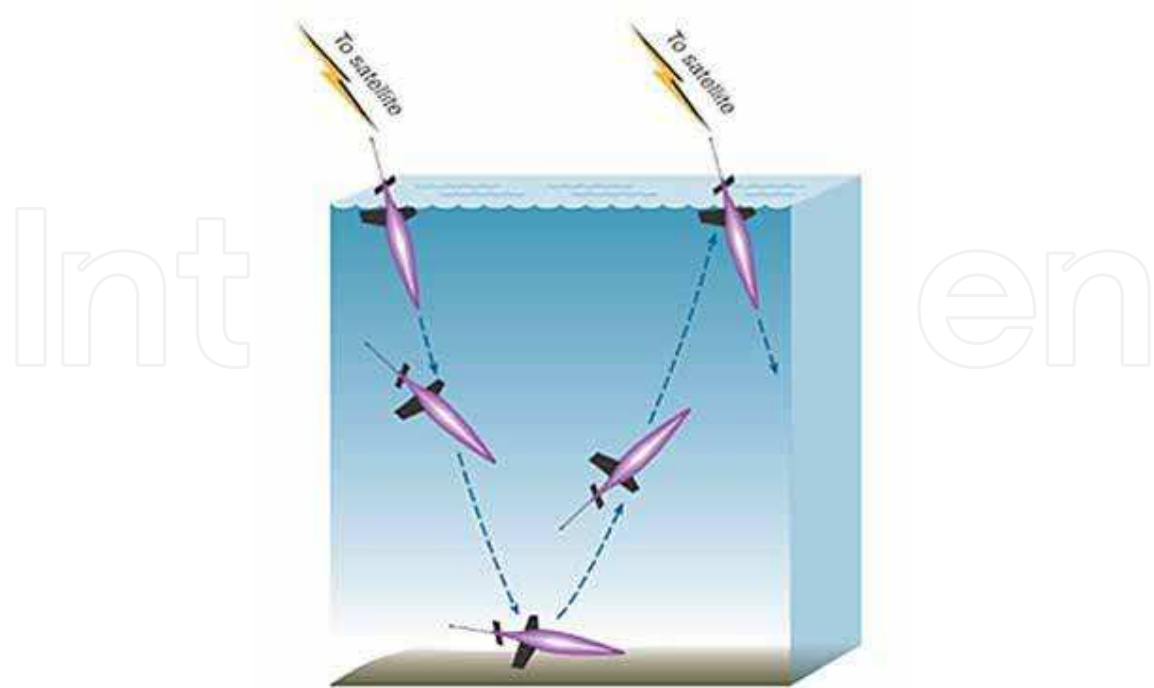

Fig. 4. Spray Schematics (Spray, 2008b)

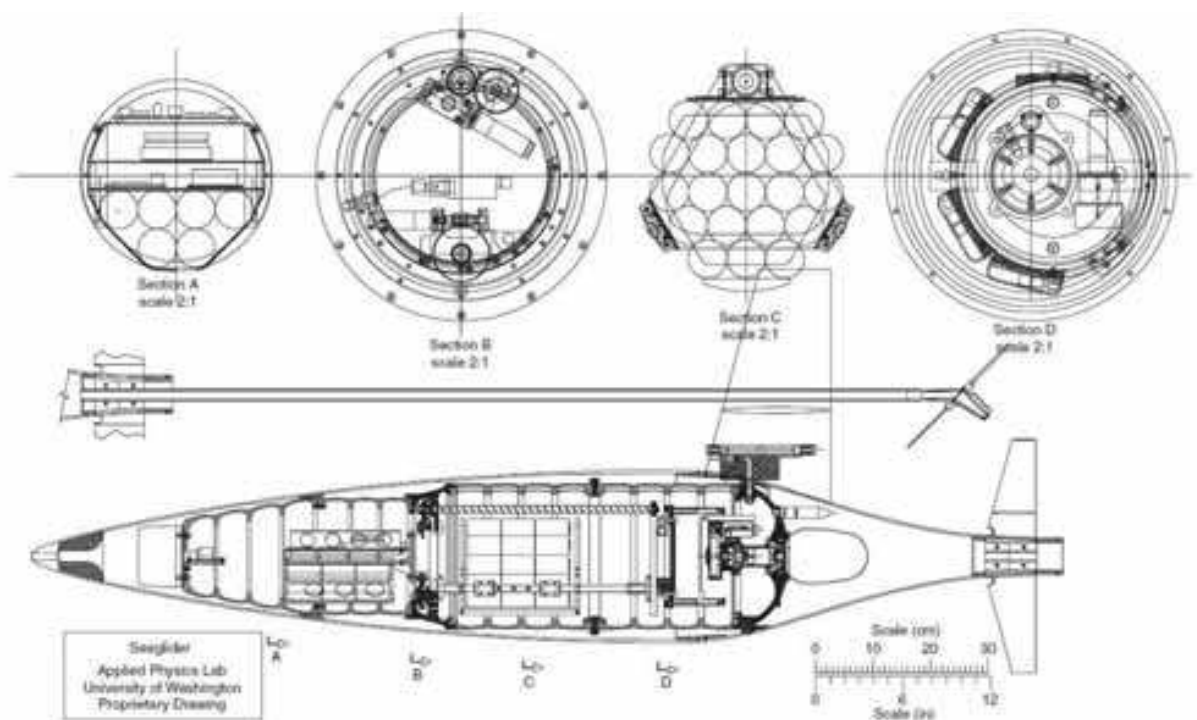
Fig. 5. Seaglider's method of travel (Seaglider, 2008)
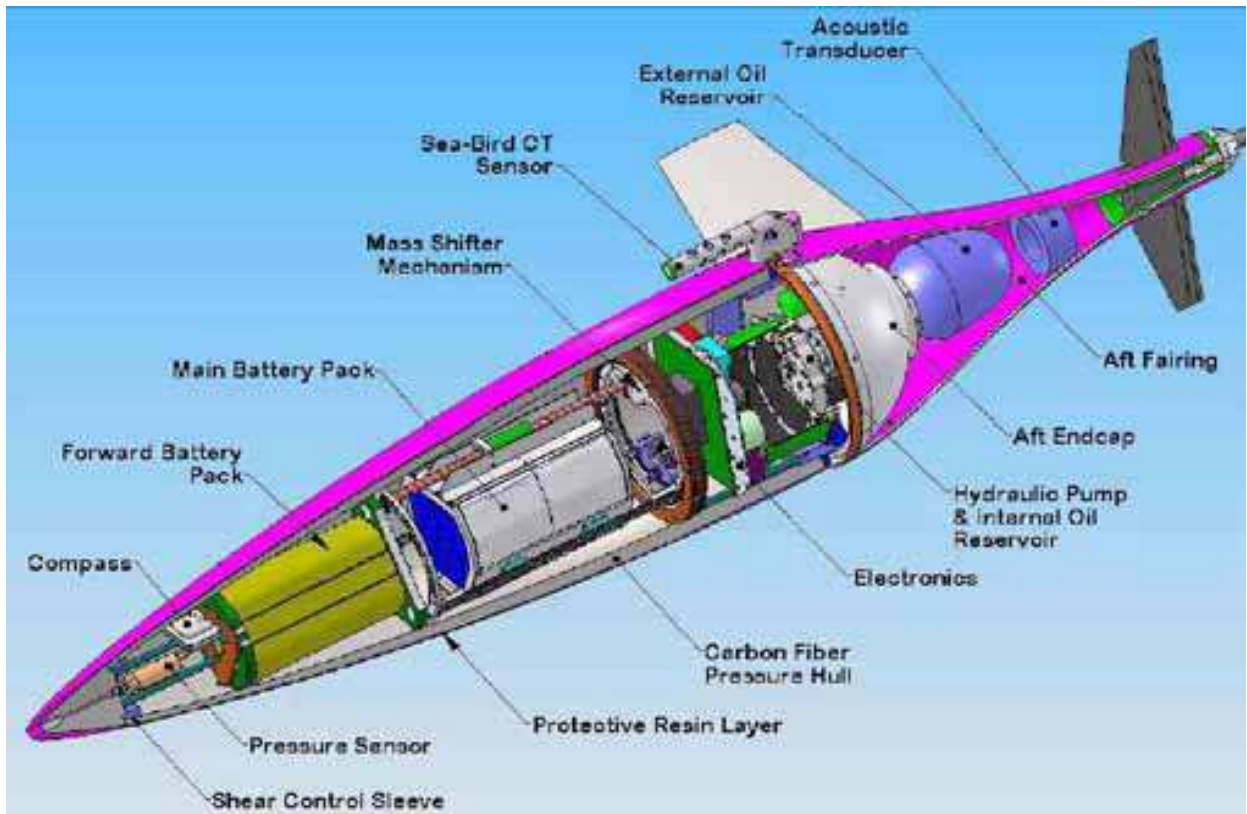
Fig. 6. Seaglider Schematic (Griffiths, 2002)

Fig. 7. Deepglider (Osse et al., 2007)

Slocum Thermal Glider

The Slocum Thermal glider (see Figures 8 and 9) was developed and optimized for long duration missions with a well-developed thermocline. The propulsion of the vehicle is

derived from harnessing the energy of the thermal gradient between the ocean's surface and bottom for use as the vehicle's propulsion. "In missions with electric-powered gliders, 60--85% of the energy consumed goes into propulsion, so a thermal-powered glider may have a range 3--4 times that of a similar electric-powered vehicle. Except for its thermal buoyancy system and using roll rather than a movable rudder to control turning, Slocum Thermal is nearly identical to Slocum Battery" (Griffiths, 2002).

The Slocum Thermal glider uses the change in volume from a material's (ethylene glycol) freezing and melting as the means of vehicle propulsion. The vehicle begins to descend by venting the external bladder into an internal bladder using the pressure difference between the two chambers (i.e., the hull/ internal bladder, filled with Nitrogen, is slightly below atmospheric pressure). As the vehicle passes through the freezing point of the material during its descent the contraction of the material causes the fluid in the internal reservoir to be drawn out into a heat exchanger. To ascend the pressurized material in the heat exchanger is transferred to the external bladder causing the vehicle to switch from negative to positive buoyancy. As the vehicle ascends the warming of the ocean waters cause the material to melt and expand further increasing its buoyancy. The vehicle arrives at the surface with the same conditions it had at the start, i.e. in a stable thermal equilibrium with the external bladder inflated, the material expanded, and the internal bladder at a slightly negative pressure. The material and pressurized nitrogen is at a slightly greater pressure than the external ocean pressure. The thermodynamic stages of the system can be seen in Figure 10.

Slocum Thermal (Webbresearch, 2008b)

- Weight: 60 kg
- Hull Diameter: 21.3 cm
- Vehicle Length: 1.5 m
- Wing Span: 120 cm
- Depth Range: 4 – 2000 m
- Payload: 2 kg
- Speed: 0.4 m/ sec horizontal (projected)
- Energy: Thermal engine, Alkaline batteries for instruments, communication and navigation
- Endurance: 5 years
- Range: 40,000 km
- Navigation: GPS, internal dead reckoning, altimeter
- Sensor Package: conductivity, temperature, depth
- Communications: RF modem, Iridium satellite, ARGOS

The Spray, Slocum (Battery & Thermal), Seaglider and Deepglider are very similar in size and general characteristics. They were designed with the same objectives, specifically in being small and easily deployed and recovered by only a couple of people. The vehicles were to be slow and the propulsion using only buoyancy control envisioned by Douglas Webb and Henry Stommel. The vehicles are dependent on the energy efficiency and glide trajectory angle during each traverse to monitor the ocean. Currently, various institutions (e.g., the University of Southampton, Great Britain) are starting the investigation of long-duration, highly efficient, slow-speed, powered autonomous underwater vehicles. These investigations will lead to the development of new highly optimized efficient wings. The optimum vehicle to handle a saw-tooth method of data sampling, as well as a vertical and

horizontal means of sampling will be some form of hybrid vehicle with a glide and a power mode that takes each sampling means into account.
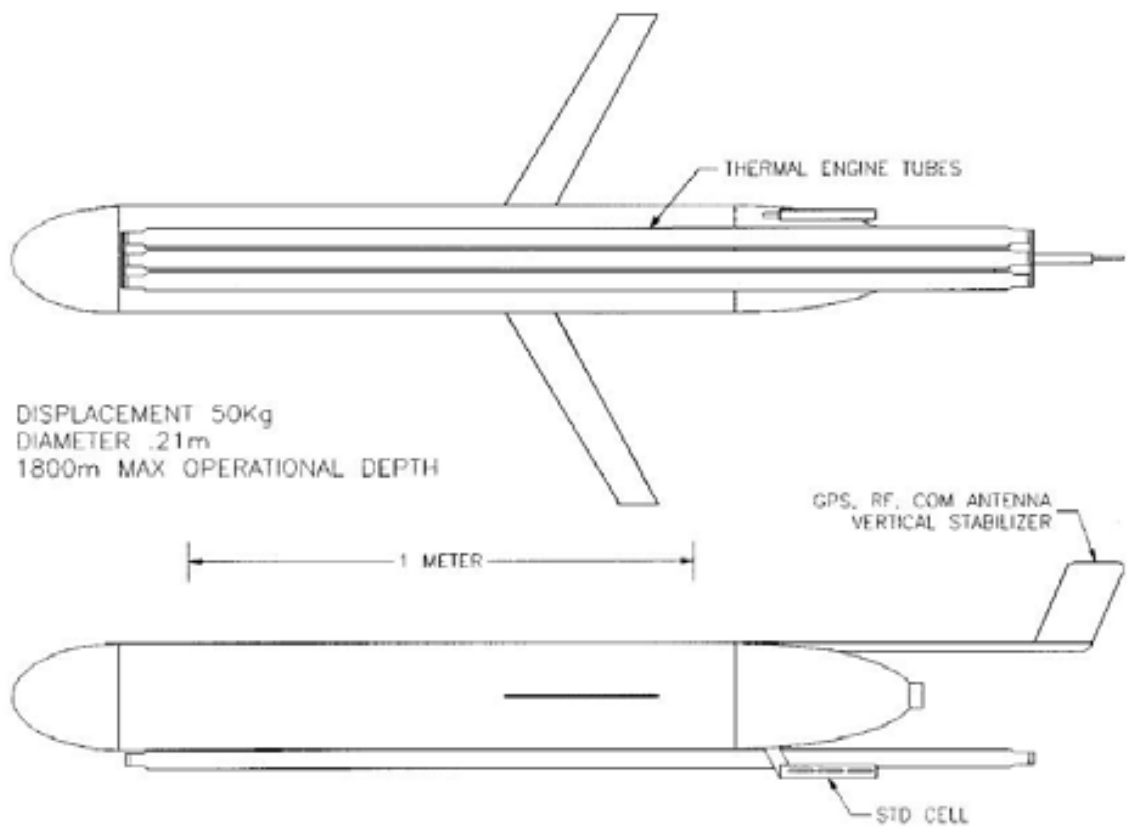

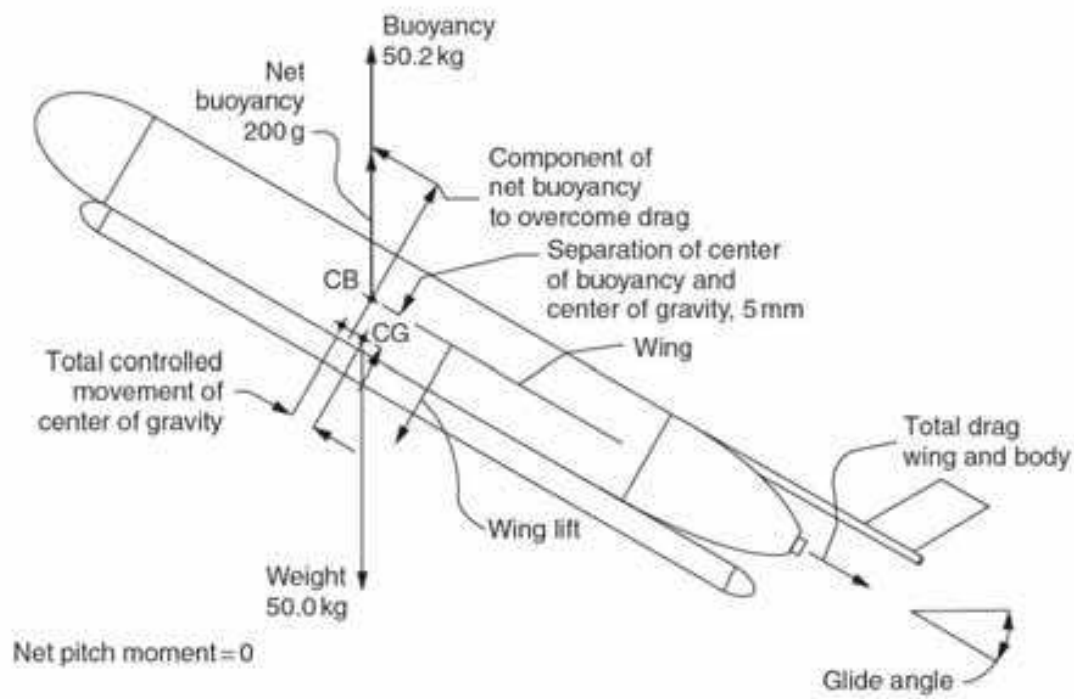Fig. 8. Slocum Glider Schematic (Webb et al., 2001)

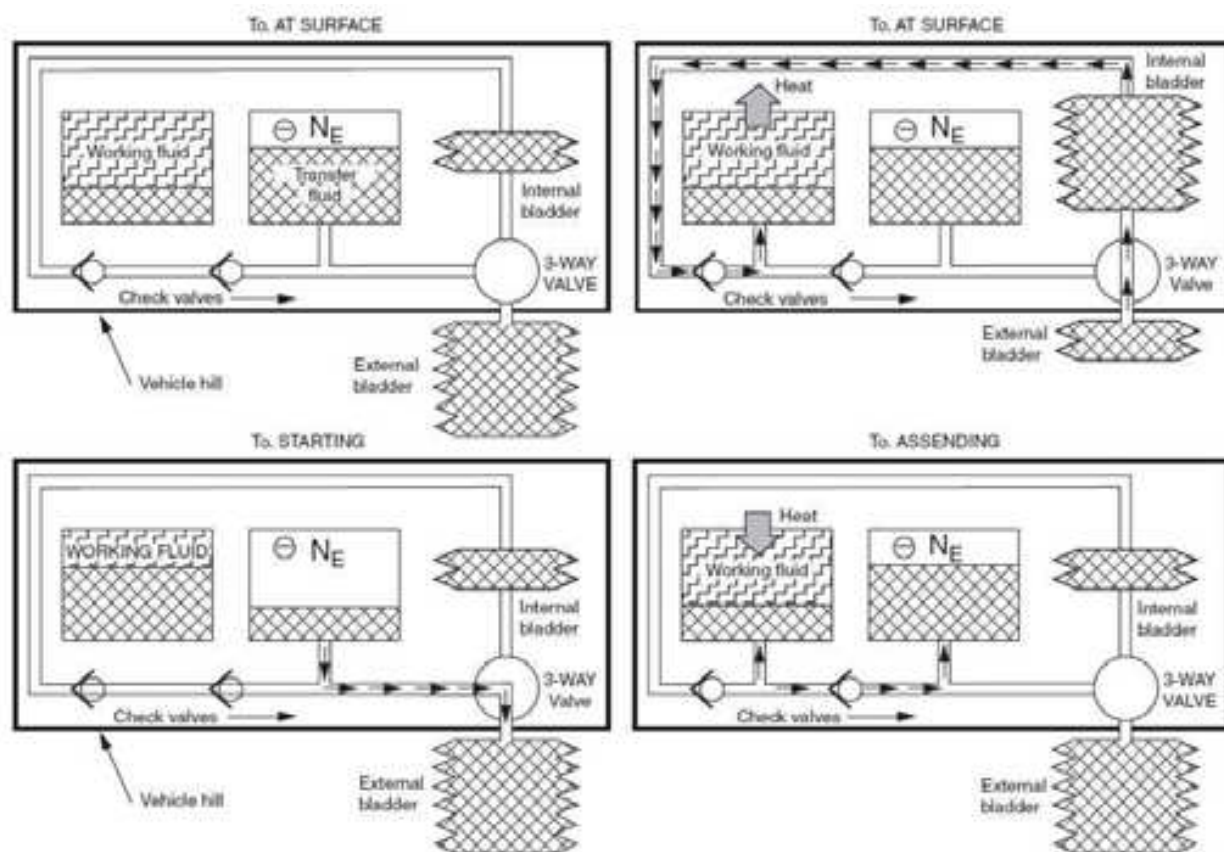Fig. 9. Slocum Thermal - Gliding forces on the vehicle (Webb et al., 2001)

Fig. 10. Slocum Thermal Cycle (Webb et al, 2001)

3. Military vehicles

The military has developed an advanced underwater winged glider based on the air force's Flying Wing design, the Liberdade XRAY (see Figure 11). This vehicle is "being developed as a part of the Navy's Persistent Littoral Undersea Surveillance Network (PLUSNet) system of semi-autonomous controlled mobile assets. PLUSNet uses unmanned underwater vehicles (UUVs) and autonomous underwater vehicles (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" (ONR, 2006).

The XRAY was develop 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 institutes, universities and corporations: University of Texas at Austin's Applied Research Lab, Applied Research Lab at Penn State University, MIT, Woods Hole Oceanographic Institute, Harvard University, SAIC, Bluefin Robotics, Metron, Heat, Light, and Sound (HLS) Research, and the Space and Naval Warfare (SPAWAR) Systems Center in San Diego.

The vehicle is the largest of all of the underwater gliders (6.1 meter 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 the new fuel cell submarines operating in shallow-water. According to military doctrine it can "be deployed quickly and covertly, 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" (ONR, 2006).

Fig. 11. XRAY Glider (APL, 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 which is better than existing gliders. Liberdade XRay's first major ocean test was performed in August 2006 in Monterey Bay, California, where it reported real-time via an 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 to 1 glide slope ratio (D'Spain et al., 2007). Later deployments were in the Philippine Sea, near Hawaii, and in Monterey Bay using the hydrophone array "to detect low frequency source signals, marine mammals (blue and humpback whales), and ambient ocean noise" (APL, 2007). The XRay glider is hoped to achieve 1–3 knot cruise speeds, have a 1200–1500 km range, and be able to remain on-station up to 6 months in partial buoyant glides.

4. Other vehicles

WaveGlider

Another vehicle that will soon come to market is Liquid Robotics' entirely new autonomous ocean vehicle "WaveGlider" that harvests all of its energy from waves and sun. The concept is a shallow water vehicle that uses the ocean waves as its primary energy source to propel it through the water. During the spring and summer of 2008 the WaveGlider underwent extended periods of field testing in the Pacific Ocean.

The design consists of a surface float (similar to a surfboard) that is tethered to a sub-surface glider about 7 meters below the surface. This subsurface glider looks similar to the Slocum glider (i.e., a torpedo hull with a simple rudder), except instead of one pair of wings there

are six sets of wings down the vehicle's side. The wings have a mechanism that "ratchet" in such a way that when a wave at the surface lifts the float, the entire system (float and glider) rises while the wings stay horizontal. As the wave passes by, the glider sinks and the wings pivot to create a downward pitch which causes 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 system moves forward in a "saw-tooth" pattern corresponding to the waves. The surface-float shoots forward in small bursts across the water controlled by the rudder. The vehicle requires at least seven (7) meters of water and a minimum wave height to operate. It has high-endurance, 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, consequently, it can traverse 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[3] and high currents are a problem.

The WaveGlider's surface float houses most of the electronics (i.e., navigation and communication equipment) along with solar cells to recharge the electronic battery packs. Only wave motion is used for propulsion. The vehicle is quite remarkable and Harbor Branch Oceanographic Institute is expected to develop a mobile observatory, in other words, a distributed sensor network for surface sensing using these vehicles. Additionally, they are hoping to demonstrate the swarming technologies that the engineering division at Harbor Branch has been working on with these vehicles (Frey, 2008).

ALBAC

One of the first gliders, the ALBAC conducted sea trials at the Suruga Bay of Japan in 1992. The vehicle, developed at the University of Tokyo in the lab of Tamaki Ura, does not have an active buoyancy control system, but 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," 120 cm in wide, "weighs 45 kg, and can dive to depths of 300 m at speeds of one to two knots (.5 to 1.0 m/s). It has horizontal tail fins which 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 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" (Graver, 2005).

The vehicle glides horizontally by up to 20 degrees 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-liter dry pay load space for scientific measurement devices. It consists of a 1/2 ellipse shaped front cap, a cylindrical pressure hull, a corn shape tail cap

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[3] No technical data of this vehicle has been released at printing.

with a vertical stabilizing fin, a pair of wings, tail wings and various electronic devices, i.e., 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 the tail caps (Kawaguchi et al., 1993).
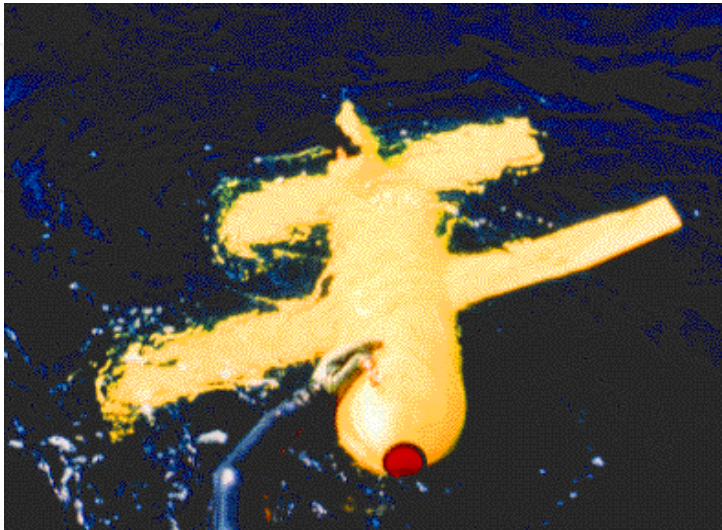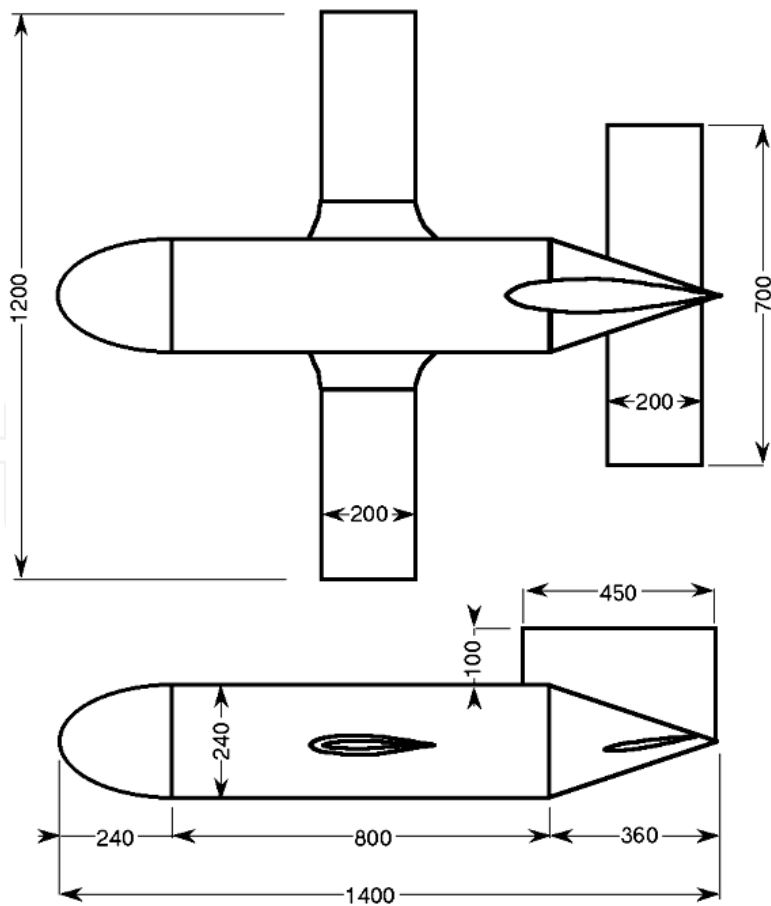

Fig. 12. ALBAC Glider (Kawaguchi et al., 1993)

Fig. 13. ALBAC Glider Schematics (Kawaguchi et al., 1993)

Hybrid AUV-Powered Gliders
AUV-Powered-Glider

Another glider under development is a hybrid, which is designed to travel under power, glide mode or both. This vehicle, under development at Florida Institute of Technology, Melbourne Florida, 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.

The AUV-Powered Glider was design using the following parameters:

- Mission applications to 6000-meter ocean depths.
- Modular design: to ship easily in small boxes and to have interchangeable scientific modules.
- Quick assembly & disassembly of AUV components.
- Easy battery access for replacement and recharging during missions.
- Reasonable space for scientific & instrument payload.
- Capable of landing

Unlike torpedo-shaped survey AUVs, the structure of the AUV-Powered Glider has a rectangular frame that is approximately 1.5 by 2-meters square. Figure 14 shows an overview of an AUV-Powered Glider prototype with the main components.
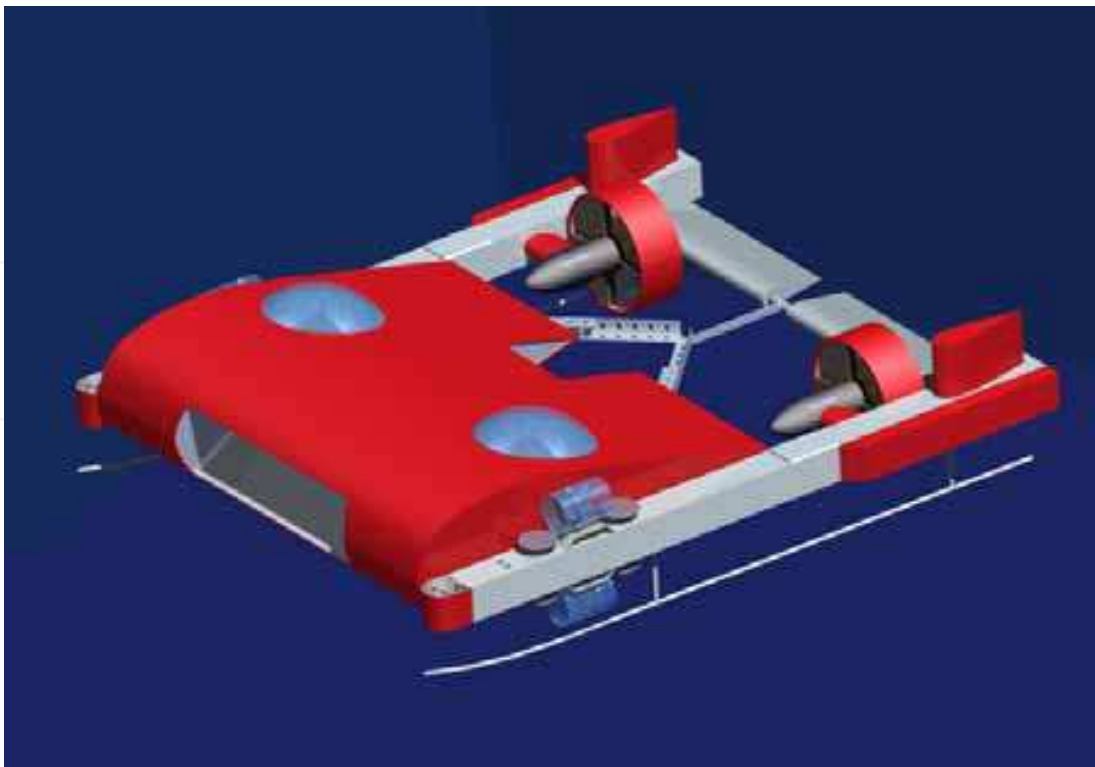

Fig. 14. AUV-POWERED GLIDER Prototype Overview

The vehicle is designed for easy assembly and disassembly, with easy access to the batteries and the two 17-inch diameter, 3/8-inch-thick vehicle control system and scientific pressure housings. The objective was to use cost-effective solutions to keep the overall budget of the vehicle reasonable. The version shown in figure 14 is for marine biologists, biological oceanographers and other scientists needing samples and photographs of organisms in the water column.

The main vehicle specifications for the AUV are:

- Dry weight: 293 kg   (without instruments and drop weight system)
- Length: 1.93 m
- Width: 1.59 m, at flares 1.69 m
- Max. Height: 0.58 m
- Displacement: 379 kg
- Maximum depth: 4000 m
- Glass pressure housing depth: 6000 m

The AUV-Powered Glider is equipped with two 12-Volt longitudinal and two 12-Volt DC-brushless vertical thrusters mounted on the forward two corners of the frame.

- Longitudinal thrusters: asynchronous 3-phased, oil-filled design.
- Optimum running speed of 2-knots.
- Estimated power usage for the two thrusters at 2-knots, 12-Volts and 5-Amps = 50-Watts for each thruster.
- Vertical thrusters: Elcom ST N2312, coil-type 3-phase wye-wound, low speed, low operating voltage and high torque (K_t=5.30), 12-Volt DC-brushless motors from DC-brushless thrusters, are typically run up to 75% thrust and draw a total of 1.0-Amp for very short periods of time (e.g., one minute to raise the vehicle's bow from the ground in cases where the vehicle has landed).

Active Buoyancy Control - is used to make the vehicle's buoyancy either slightly positive or negative allowing the vehicle to glide up and down the water column in a saw-tooth pattern. The speed of the ascent or descent in glide mode depends on the buoyancy and glide angle and whether the vehicle is under power. The vehicle can be under power at any time, but energy consumption is high since the motors use more energy than any individual system on the AUV. A simple drop weight / drop float system is integrated currently for rapid prototype development allowing the vehicle 10 glide cycles. The design and development of a deep water buoyancy system is a primary task for future development of this vehicle.

Active Trim Control - is used to actively to control and stabilize the vehicle's trim. For example, when the buoyancy system has an unbalanced configuration (e.g., too much positive or negative buoyancy on one side) or when something foreign is tangled with the vehicle such as seaweed, the active trim control would attempt to align the vehicle. This control is handled by the rear control rudders and flaps. An automatic trim system using liquid mercury is under investigation that is similar to the trim systems on airplanes.

Fluid Intake Channel - at the front of the vehicle focuses water and organisms from in front of the vehicle through the channel. Two camera systems document what passes through the channel: one mounted so the photos are made from the side of the channel; the other mounted facing directly into the channel. An optional mesh can be mounted in front of the camera to collect organisms over a specified distance. The vehicle would reverse direction to wash already documented samples from the screen using the vehicle's thrusters.

Sample Taking - is made through a limited number of small sample chambers mounted along the external frame allowing the scientist to obtain permanent samples of the water and biological organisms. The sample chamber is opened and closed by servo motors at pre-set times.

Communication - is via a 802.11b Wireless Ethernet (WLAN) card between the AUV and a host PC allowing wireless communications with the AUV while at the surface and via radio through a MaxStream 9Xstream-PKG-R low-speed, half-duplex radio modem, with an extended range at sea: 7 miles (11km). Information concerning the MaxStream can be found at: (MaxStream, Inc., http://www.maxstream.net/).

Navigation and Absolute Positioning - is made with a Spartan Electronics SP3000D digital compass, depth gage and speed vector/altitude generated by a Doppler Velocity Log (DVL) for dead reckoning. Like any integrating process, dead reckoning accumulates errors and requires periodic fixes to cancel resulting drift. This is done by GPS during surface navigation. Collision control is through two UA-2 altimeters from JW. Fishers Mfg., Inc. The altimeters have the pulse generation and return detection circuitry potted into the transducer and return the information to the computer via a RS232 connection. The UA-2 altimeters provide height over ground and the distance to an object in front of the vehicle up to 100 feet (30 meters) at 200 kHz. An inertial measurement unit (IMU) will measure the vehicle's acceleration and will determine the vehicle's position while underwater. The position will be verified by GPS when the vehicle is on the surface.

Control System and Supervision (See Figure 15) - algorithms manage the entire vehicle with a combination of a traditional feedback system and an under-development neural-network control system is used standard grid pattern surveys and chemical or physical trace mapping.

Sterne Hybrid Glider

The Sterne glider, developed at Ecole Nationale Superieure D'Ingenieurs in Brest, France is a hybrid glider having both a glider (buoyancy) and thruster mode. The 4.5 m long, 0.6 m in diameter, 900 kg in mass vehicle has buoyancy control and a thruster for forward propulsion and 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 120 miles with an estimated speed of 3.5 knots (1.8 m/s). The vehicle has 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).

5. Scientific sensors

An autonomous oceanographic data acquisition vehicle/glider that is usable by a wide range of scientists must be able to accommodate many different scientific instrumentation configurations, be capable of collecting specimens and be able to perform the missions as specified. Sensor packages are instrumental to a vehicle. Slocum, Spray, Seaglider and WaveGlider are too small for use with many types of instruments. Additionally, the saw-tooth 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 autonomous underwater vehicles that are rated down to 6000 meters are: **Sidescan sonar, Falmouth Scientific NXIC CTD** (a fully integrated
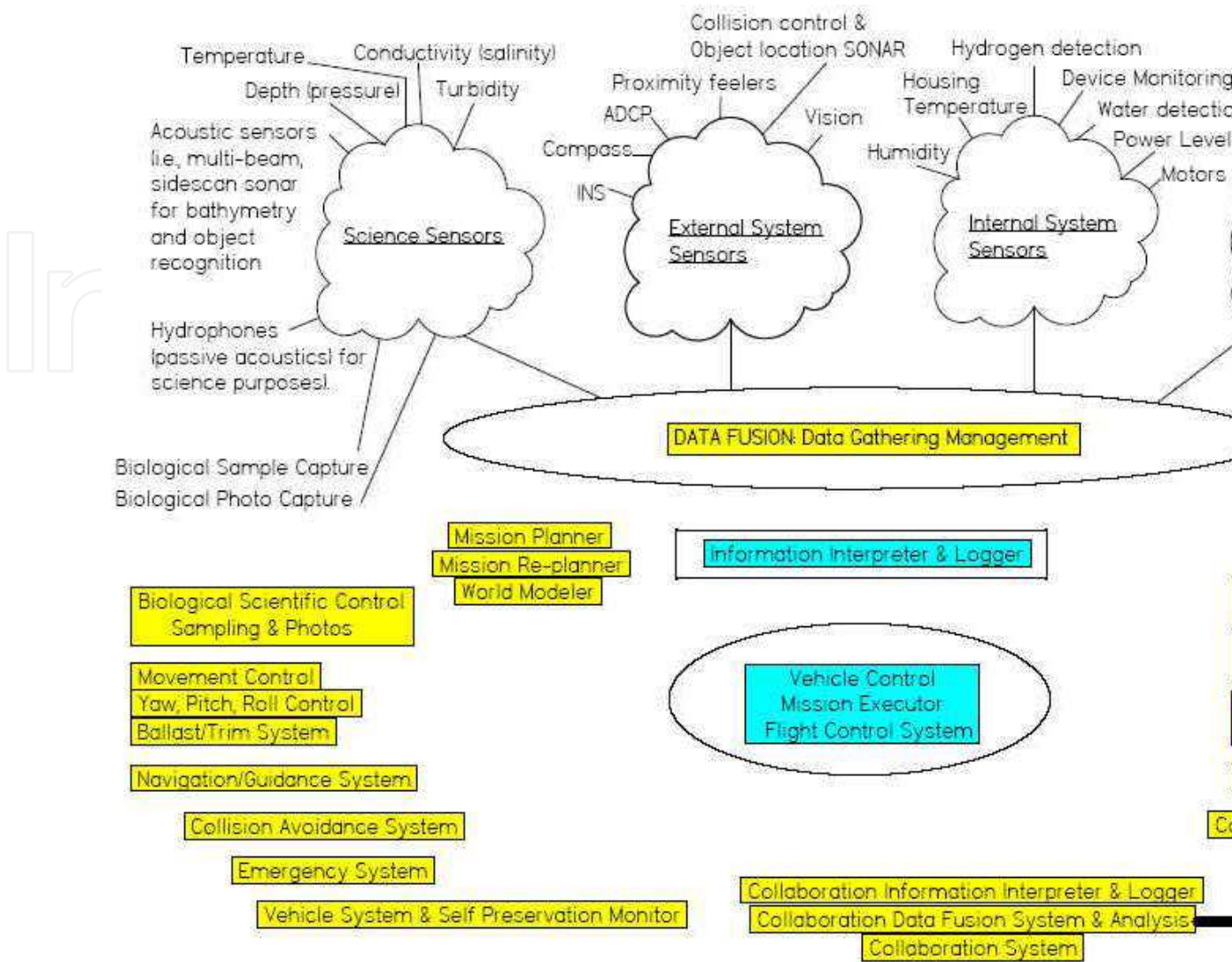
Fig. 15. AUV-Powered Glider's Autonomous Underwater Vehicle Systems Diagram

instrument platform (compact, robust and equipped with fully integrated conductivity, temperature, and depth sensors) with battery-power, internal data logging and external sensor input capability. It is designed to meet the demands of open-ocean, estuarine and fresh water environmental monitoring. It can be operated to a depth of 7000 meters and data may be stored on the internal storage memory or transmitted in real time via a serial interface (information available at http://www.falmouth.com/).); **Chelsea AQUA**_tracka_ **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, fluorescein. The AQUA_tracka_ III is designed for depth up to 6000-meters. Applications: chlorophyll-a and other fluorophor detection, rhodamine and fluorescein dye tracing, particle concentration by light scattering, profiling, towed, moored or ROV deployment, pollution monitoring, bio-geochemical oceanography, and hydrothermal vent studies. This instrument can sense chemical fluorescence or light scatter in the visible and near infrared (400 to 800-nm). Versatility is achieved by the selection of appropriate optical narrow bandpass filters to match the excitation and emission wavelengths of the fluorophor, e.g., chlorophyll-a, rhodamine or fluorescein. It may be configured as a nephelometer by using the same bandpass filters for both excitation and emission.), **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. The image data will be used, among other things, to qualify the initiated measurement locations offline and therefore document the measurement procedure), and **acoustic hydrophones**.

6. Future

As autonomous vehicles are developed to take on more responsibilities, program algorithms will be developed to accommodate these tasks. Currently, as mentioned in the WaveGlider section, 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 "swarm" capabilities among multiple vehicles. With on-board collaborative control, the vehicles operate as a group, functioning together as a "swarm." The swarm processes and communicates relevant information allowing individual vehicles and the entire swarm (i.e., group) to change direction, autonomously, in response to sensor inputs. This control is one of the primary research initiatives by the military for unmanned vehicle control in the air, on the ground and underwater. The concept of swarming is also useful to science for the sampling of entire regions for a specific organism, substance or phenomenon. The control of an autonomous underwater vehicle whether powered or a glider will also in the future utilize some combination of traditional (Figure 16) and neural network (Figure 17) navigation system that uses Kalman filters[4] to control the AUV.

One of the requirements for a long duration, autonomous underwater vehicle, 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

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[4] A Kalman filter is a recursive filter estimating the state of a dynamic system. It is especially useful for handling incomplete or noisy measurements.

distances and the relative velocities will be by the use of the positioning data as well as by 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 the AUVs can give further important information for the positioning prognosis.
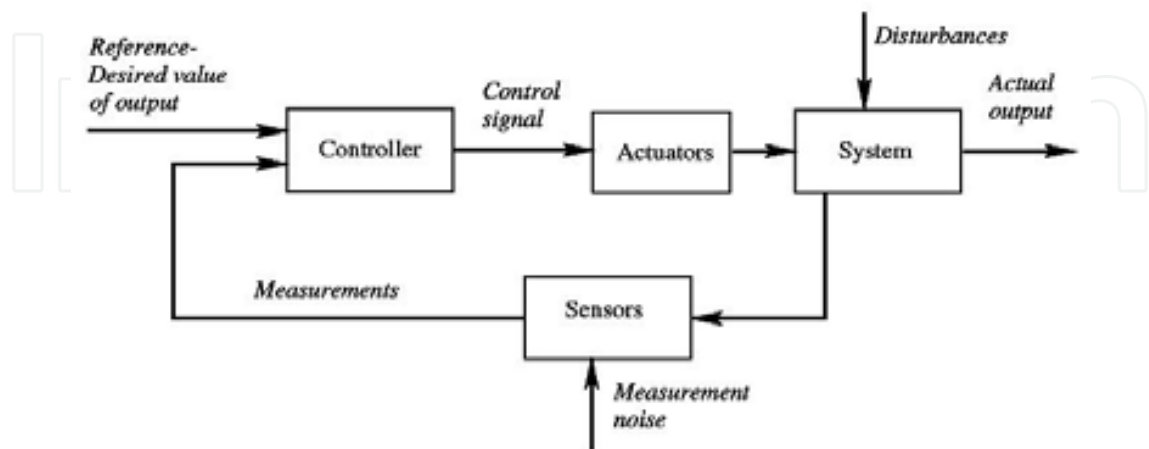

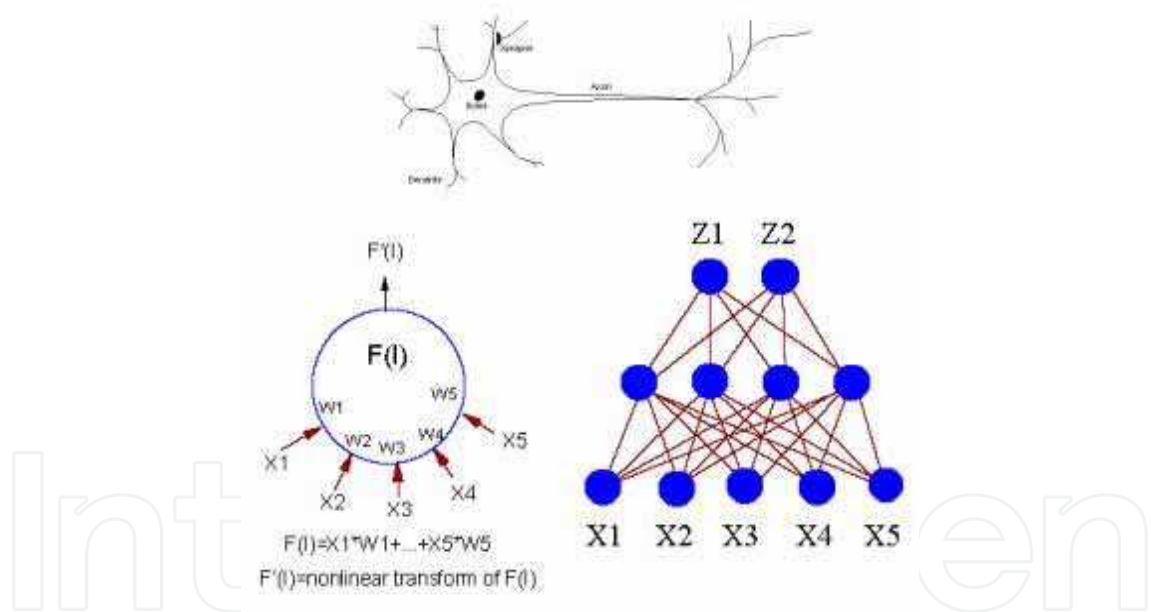Fig. 16. Traditional Feedback System with Sensors

Fig. 17. The neural networks for control systems are based on human brain structure. The networks consist of artificial neurons, and each neuron is connected to other neurons through weights.

Current thruster powered commercial AUV systems use a combination of internal inertial, compass, and accelerometer sensors, in conjunction with external active acoustic triangulation methods (LBL, SBL, USBL)[5]. These have met with some success for applications of cable following, standard grid surveying, search and rescue, or signal

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[5] LBL – Long Baseline, SBL – Short Baseline, USBL – Ultra Short Baseline.

following. But in each of these cases, the system is unable to respond to a) abrupt changes in external environment, b) system damage, 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 (Wilson, 1995) 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) causes 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 autonomous underwater vehicle (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, there are many problems these vehicles are only beginning to address. Examples of these might include: search for environmental pollutants; search and analyze biological systems; locate and identify artificial acoustic sources; long term scanning for physical, biological, or chemical subjects of interest; non-inertial navigation.

The final step in the process is to use the processed multi-sensory data from the pattern recognition and data classification modules to provide control inputs for the navigation system. Thus, the system would then be able to track and monitor targets as listed above. In this phase, a simple feedback of neural network outputs will be sent to the control processor algorithm. The power of the neural network paradigm is the ability of the system to integrate the sensor input from a variety of sources into multi-sensory patterns, that is, acoustic with salinity, temperature and pressure, spectrographic with temperature, etc. But instead of traditional analytical methods where the individual datasets are correlated one by one, the neural network will be able to search for patterns in all sets together.

7. Conclusion

Autonomous Underwater Vehicles are only now being marketed as robust commercial vehicles for many industries, and of these vehicles underwater gliders are becoming the new tool for oceanographers. Satellites have provided scientists and marine specialists with measurements of the sea surface such as temperature since the late 1970s, and data via subsurface oceanographic moorings since the 1950's. As stated by David Smeed of the National Oceanography Centre, Southampton, England, *that* "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" (Douglas, 2008).

The Southampton team deployed a Slocum Glider on the 16th of September 2008 in the Eastern Atlantic (launched from the Canary Islands with the co-operation of the Instituto Canario de Ciencias Marinas (the Canarian Institute of Marine Science) with the aim of determining the interaction between oceans and climate and the intent to improve the ability of the scientist to detect signs of rapid climate change. That vehicle is expected to

travel 2,300 km over 90 days with a minimum of 1,000 profiles collecting temperature, conductivity (salinity), depth and current in its 1,000 meter depth range. The data retrieved will be made available to "the 'Rapid-Watch' program that monitors the meridional overturning circulation of the Atlantic. Also known as the 'Atlantic heat conveyor' this is the system of ocean currents that transports heat polewards, thereby influencing European climate" (Douglas, 2008).

The Rapid-Watch program is tasked to observe the Atlantic through 2014 with oceanographic moorings, ship observations and now autonomous underwater gliders. As stated by David Smeed, "the Rapid-Watch program is teaching us a great deal about how to monitor and evaluate changes in the ocean and climate. Underwater gliders are going to expand our capability to make these important measurements and enable us to get the data we need more efficiently."

Another important initiative is the "**The European Gliding Observatories (EGO) initiative,**" which is composed of oceanography teams from France, Germany, Italy, Norway, Spain, and the United Kingdom (but not restricted to European partners only) who are interested in developing the use of gliders for ocean observations throughout the world. More information concerning this initiative and becoming a member can be found at < https://www.locean-ipsl.upmc.fr/ gliders/ EGO/ >

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Underwater Vehicles

Edited by Alexander V. Inzartsev

For the latest twenty to thirty years, a significant number of AUVs has been created for the solving of wide spectrum of scientific and applied tasks of ocean development and research. For the short time period the AUVs have shown the efficiency at performance of complex search and inspection works and opened a number of new important applications. Initially the information about AUVs had mainly review-advertising character but now more attention is paid to practical achievements, problems and systems technologies. AUVs are losing their prototype status and have become a fully operational, reliable and effective tool and modern multi-purpose AUVs represent the new class of underwater robotic objects with inherent tasks and practical applications, particular features of technology, systems structure and functional properties.

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