A New Platform for Offshore Exploration and Production

Accurate data are essential for developing climate models and weather forecasts used in planning offshore E&P operations. A new remotely controlled, autonomous marine vehicle has been developed to carry a variety of sensors for conducting detailed meteorological and oceanographic surveys across vast distances and under extreme conditions. The role of this new sensor platform is expanding to support an even broader range of missions.

The oceans cover more than 70% of the Earth’s surface and have played a dominant role in its geologic history. Although the oceans contain a substantial portion of our planet’s natural resources, their depths remain largely unexplored. Long-term monitoring over vast expanses of ocean may lead to better understanding of processes that continue to shape the planet while helping scientists discover new resources and predict the impact of ocean forces that could disrupt commerce or alter the course of everyday life.

Forces of nature, such as hurricanes and typhoons, pose a recurring threat to thousands of communities along the coast; earthquakes and tsunamis occur less frequently but often cause more damage. Sweeping events and weather patterns influenced by the ocean not only menace coastal dwellers but also impact industry and commerce around the world. The oil and gas industry feels the effects of weather in seasonal demand fluctuations. In the offshore environment, the effects of weather translate into concessions that operators must make: Is it prudent to mobilize a drilling rig, are the waves too high to offload equipment, or are the winds too strong for helicopter operations? Meteorological and oceanographic, or metocean, data—especially height of waves and period of swells, speed and direction of wind and surface or subsurface currents—provide crucial input for planning rig moves and placement. Geophysical survey crews must assess the effects of tides and currents on the feathering of seismic streamers as they are towed through the water. Wave height is a key parameter used in designing production platforms, and pipelines must be installed to withstand subsea currents. Ocean monitoring plays an integral role in risk assessment and management by providing information that helps forecasters, planners and field personnel assess the degree to which they must accommodate forces of nature.

But monitoring is often a costly proposition. Conventional sensor platforms such as buoys, ships, aircraft and satellites are expensive and require extensive lead time for planning, procurement and construction. Personnel to support these platforms and their missions must also be trained and managed. Satellite-mounted sensors and storm-chaser aircraft evaluate the air column and ocean surface but are limited in their on-scene endurance, real-time sampling data rates and capability to measure conditions at or beneath the sea/air interface. Oceanographic ships can range over great distances while taking a variety of measurements, but vessel and crew are not meant to withstand extreme conditions and also must return to port for replenishment after a limited time. Ocean-observation buoys can also be outfitted with sensors but are anchored in place, so they measure conditions within only a relatively fixed location. The cost to build, deploy or crew a metocean survey platform often starts in the millions of dollars and increases with the intricacies, risks or ambitions of the mission.
One complement, and in some cases alternative, to satellites, planes and ships is an unmanned mobile sensor platform for monitoring ocean conditions. This concept is part of a progression that led to development of remotely operated vehicles (ROVs), which have become essential inspection and intervention devices for deepwater oilfield operations. With one or two skilled pilots at the surface, the ROV can wield the tools and power to carry out complex tasks in a forbiddingly dark, cold and high-pressure environment. Some ROVs eventually dropped their command and control umbilicals to take commands through subsea telemetry; now autonomous underwater vehicles (AUVs) are routinely used in subsea surveys. These unmanned vehicles have helped expand the envelope of deepwater operations and have been instrumental in increasing productivity and safety in one of the most hostile environments on Earth. These vehicles, however, require support from the surface.

The Wave Glider autonomous marine vehicle (AMV), developed by Liquid Robotics, Inc., is a hybrid sea-surface and underwater vehicle that has taken the concept of autonomy beyond that of the AUV. This wave-powered sensor platform enables collection and transmission of data gathered at sea on missions lasting up to a year. It is capable of crossing thousands of kilometers of ocean to gather oceanographic data, taking meteorological readings while maintaining a stationary position, or circling a rig at a preset distance to provide early warning of security or environmental threats. Once deployed, it uses no crew, requires no fuel and produces no emissions, thus eliminating both risk to personnel and impact on the environment. For much less than the cost of a moored buoy or a vessel and crew, the Wave Glider vehicle provides mobility and long-range endurance for extended ocean monitoring missions. It has already carried out hundreds of missions ranging from the Arctic region to Australia and from the Canary Islands to Loch Ness in Scotland.

This article discusses the development of this multimission, autonomous sensor platform and describes its applications—from measuring meteorological parameters to detecting oil seeps. Examples from the Gulf of Mexico and other areas demonstrate how persistent, unmanned mobile monitoring platforms have proved beneficial to offshore exploration and production efforts.

2. Feathering is the lateral deviation of a seismic streamer away from its intended towing direction as marine currents push the streamer off course.
3. The exact diameter of that fixed location is defined by the watch circle of the buoy’s anchor system, which is a function of the length of chain attaching the anchor to the buoy. To withstand extremes in tides and wave height, the buoy is anchored with steel chain whose length is typically three to five times the water depth. Although this extra chain serves to reduce shock loading on the ground tackle used to anchor the buoy, it also means that the exact position of a buoy will vary with the tides, winds and currents.
6. In 2012, Liquid Robotics, Inc. and Schlumberger created a joint venture known as Liquid Robotics Oil & Gas to extend autonomous marine vehicle services to the oil and gas industry.
The Wave Glider AMV uses wave energy for thrust, while solar energy powers its rudder motor, navigation system and payload electronics. This AMV consists of a surface float and a submerged glider connected by an electromechanical umbilical (above). Each of these parts can support an array of sensors to create a custom payload for each mission. The float weighs about 68 kg [150 lbm] including a typical payload.

The float measures 208 by 60 cm [82 by 24 in.]. Its deck supports antennae for GPS, satellite communications and collision avoidance systems, as well as a mast to support a position marker light and flag for increased visibility. Its surface also holds two photovoltaic panels that continually replenish the lithium-ion batteries used to power the vehicle’s navigation, communication systems and sensor payloads. Seven smart battery packs housed within the float are each electrically isolated with separate discharging and monitoring circuitry that permits only two batteries to be in use at a time. Two payload bays support a total of 18 kg [40 lbm] of sensors and equipment.

The umbilical, about 5.8 m [19 ft] long, provides a flexible connection between the surface float and submerged glider. This line also serves as a conduit for transmitting power and steering commands to the glider.

The submerged glider, or sub, is 2 m [6.5 ft] long. The sub glides on six pairs of underwater wings that propel the entire Wave Glider system forward. The sub frame supports a rudder and its control package. The frame weighs about 68 kg and can support a variety of sensors.

The low-profile surface float, high-strength umbilical and sturdy sub allow the vehicle to carry on through high winds and waves of the open ocean. The sub is sheltered from surface weather conditions and acts as a drift anchor to counter the effects of wind and wave on the surface float. The current model, the Wave Glider SV2 platform, has survived five hurricanes and three tropical cyclones and has logged more than 560,000 km [300,000 nautical mi] since 2009.

Ocean Locomotion

The Wave Glider propulsion system is passive and mechanical; it converts energy from wave motion into thrust. This propulsion system exploits the natural difference in wave motion between the surface float and the submerged glider. Articulating fins, or wings, attached to the sub convert wave energy to generate more than 1.3 kN [300 lbf] of thrust as they pivot vertically. The vehicle produces forward thrust independent of wave direction as its float moves up and down with each wave and the sub tows the float forward (next page, top).

Forward speed is dependent on the overall buoyancy force provided by the float when tethered to the weight of the sub. The vehicle’s mass and buoyancy vary with payload, so the float, umbilical and sub must be balanced and tuned to provide optimal propulsion performance. The AMV is designed to operate in variable conditions, ranging from sea state 0 to state 6 (left).

The vehicle can achieve speeds up to 1 m/s [2 knots] and in typical wave conditions of 0.5 to 1 m [1 to 3 ft] reaches 0.5 to 0.75 m/s [1 to 1.5 knots]. At this rate, it is able to travel about 1,000 km [620 mi, 540 nautical mi] in a month. It can also harvest energy from high-frequency, low-amplitude waves—such as wind ripples—so that even under calm conditions, its speed rarely drops below 0.25 m/s [0.5 knots].

This AMV has demonstrated its capability to perform in extreme sea states. One Wave Glider vehicle, designated G2, experienced a close brush with Hurricane Isaac in August 2012. The storm

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Wave Height, m</th>
<th>Ocean Surface Characteristics</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Glassy calm</td>
</tr>
<tr>
<td>1</td>
<td>0 to 0.1</td>
<td>Rippled</td>
</tr>
<tr>
<td>2</td>
<td>0.1 to 0.5</td>
<td>Smooth or with wavelets</td>
</tr>
<tr>
<td>3</td>
<td>0.5 to 1.25</td>
<td>Slight</td>
</tr>
<tr>
<td>4</td>
<td>1.25 to 2.5</td>
<td>Moderate</td>
</tr>
<tr>
<td>5</td>
<td>2.5 to 4</td>
<td>Rough</td>
</tr>
<tr>
<td>6</td>
<td>4 to 6</td>
<td>Very rough</td>
</tr>
<tr>
<td>7</td>
<td>6 to 9</td>
<td>High</td>
</tr>
<tr>
<td>8</td>
<td>9 to 14</td>
<td>Very high</td>
</tr>
<tr>
<td>9</td>
<td>More than 14</td>
<td>Phenomenally high</td>
</tr>
</tbody>
</table>

^ Table of sea states. The World Meteorological Organization categorizes the force of progressively higher seas according to wave height. The Wave Glider AMV can operate in conditions up to sea state 6.
passed within 100 km [60 mi] of G2’s location in the Gulf of Mexico. When the hurricane veered toward the vehicle, its pilot—who monitored the situation from the operations support center (OSC) in Sunnyvale, California, USA—issued a course change that took the vehicle out of danger.

Outfitted with sensors to measure water speed, air and water temperature, wind speed and barometric pressure, G2 transmitted data despite its proximity to the storm (right). More recently, in October 2012, a different Wave Glider AMV successfully piloted through 130-km/hr [70-knot] winds to transmit weather data in real time as Hurricane Sandy traveled northward along the US eastern seaboard.\(^7\) In stormy conditions, the vehicle’s performance is boosted by increased wave energy, which allows it to maintain its intended course.


\(^9\) A knot, or nautical mile per hour, is equivalent to 1.151 statute mile/h [1.852 km/h].


Station keeping capability. An open ocean observation buoy (right) was moored next to a bottom pressure recorder (BPR) on the seafloor to relay data from the BPR to scientists on shore. Although it was moored beside the BPR, winds and currents tended to push the buoy to the southeast quadrant of its 3,400-m [11,000-ft] watch circle. A Wave Glider AMV (left) was tested for its feasibility as a relay station for the BPR data.

The Wave Glider AMV can accommodate a broad range of off-the-shelf or custom sensors to fit the needs of the mission. A GPS receiver not only determines vehicle position, it provides a precise time stamp for all data recorded on the mission. Photo voltic panels keep lithium-ion batteries charged to support WiFi, cellular or satellite communications systems, onboard data processing and various payloads.

Additional sensor payloads can be configured according to client specifications:
- meteorological sensors to record barometric pressure, air temperature and wind direction, speed and gusts
- wave sensors to record wave height, period and direction
- acoustic modems to harvest data from sensors mounted on subsea structures or the seafloor
- bathymetry sensors to map water depth
- current sensors to record direction and speed
- water salinity and temperature sensors
- fluorometry systems to detect the presence of oil, turbidity and chlorophyll in the water
- magnetometers to measure the magnitude and direction of magnetic fields
- cameras to provide real time imaging; also used to monitor ice proximity or to verify the presence of surface oil sheens
- passive acoustic recorders to detect and analyze marine mammal vocalizations.

Clients can monitor vehicle status and data in real time. An account-based credentialing scheme provides security for communicating with the vehicle using the Internet. Updates are generally carried out at client-specified intervals ranging from 1 to 15 min. An onboard hard drive records higher resolution sampling rates.

Piloting by Remote Control

The Wave Glider AMV can be programmed to travel directly from one location to another or to follow a specific route defined by multiple sets of geographic coordinates, or waypoints. The onboard GPS guides the vehicle from one waypoint to the next. The vehicle uses a 12-channel GPS receiver as its primary navigation sensor, along with a tilt-compensated compass with three-axis accelerometers and a water speed sensor. This system typically provides navigation accuracy of better than 3 m [10 ft].

Alternatively, Wave Glider pilots can steer their charges remotely (next page, top). Command and control information is relayed via satellite link with a secure, web-based user interface for directing the units. The Wave Glider Management System allows pilots to issue course commands using any Internet-enabled computer or cellular telephone that supports web browsing.

Collision avoidance is crucial to the success of autonomous vehicle programs. A key strategy for the AMV is to see and be seen so that appropriate steering commands may be executed in time to avoid accidents. A mast, flag and light are typically installed to visually mark the AMV float position. More importantly, the float carries an integrated package of electronics to highlight its position. A radar enhancer produces a distinctive target on the radar screens of approaching vessels. A satellite communications system, azimuthal heading sensor and GPS are linked to an automatic identification system (AIS) for tracking vessel movement.

Commercial vessels are required to carry radar and AIS (next page, bottom). Automatic interrogation and exchange of position, course and speed data are provided by the AIS, whose data are displayed on the radar screen to help navigators on an approaching vessel track the course of the autonomous vehicle. Reciprocal AIS data are automatically relayed from the AMV to Wave Glider pilots onshore, who also monitor vessel traffic and issue AMV steering commands to prevent collisions.

E&P Applications

Wave Glider sensor platforms are suited to a variety of scientific missions and applications. Its persistence and range allow this AMV to gather time-series data across wide geographic areas, enabling scientific research that was not practical or economical using data gathered from buoys, ships or satellites.

Detection of naturally occurring hydrocarbon seeps is probably the oldest method of oilfield exploration. From a geologist's perspective, ocean surface oil is a good indicator of more reserves beneath the seabed. Ecologists and oceanographers are also interested in learning how organic carbon from these seeps might affect neighboring benthic and benthic-pelagic environments and the chemosynthetic communities they support.
Biological interactions, mixing and dissolution consume or disperse a portion of the hydrocarbons as they rise through the water column, but some hydrocarbon bubbles or droplets eventually reach the surface. There, they spread out to form a thin oil patch, or sheen, whose depth and breadth depend on sea surface conditions—particularly wave agitation, temperature and evaporation, which affect the rate of dispersion. These patches occur regularly but are often short-lived. They can be observed visually or detected by satellite-mounted synthetic aperture radar (SAR). However, orbits of SAR satellites typically permit no more than two passes per day over a particular site. Unmanned sensor platforms that measure hydrocarbons and other environmental parameters and transmit the data to shore-based researchers are an effective alternative to satellites or ship-borne measurements.

Wave Glider sensor platforms have been used during a two-month mission in the Mississippi Canyon area of the Gulf of Mexico to evaluate natural oil seeps in the vicinity of salt domes and mud volcanoes. The AMV science payload consisted of a float-mounted water speed sensor, a mast-mounted weather station, a fluorometer that measured low concentrations of semivolatile hydrocarbons and two optical sensors that measured concentrations of dissolved and suspended organic material via fluorescence. Prior to the AMV deployment, optical sensor response was calibrated to known concentrations of crude oil at various stages of weathering in a wave tank testing facility. The resulting Wave Glider sensor data helped scientists map the location and extent of the natural oil sheens.

On the other side of the world, Chevron's Environmental Technology Unit, in collaboration with the Centre for Marine Science & Technology at Curtin University in Perth, Western Australia, deployed a unique sensor configuration on two Wave Glider sensor platforms. The AMVs obtained baseline turbidity data prior to the initiation of dredging operations for a pipeline offshore Australia. Deployed in three sorties, the AMV sensor platforms carried out metocean surveys and obtained measurements to assess turbidity through areas affected by the dredging. During the first sortie, the system obtained a variety of metocean measurements, including the direction and magnitude of ocean currents, air temperature, wind speed and direction, atmospheric pressure and water temperature and salinity. These data provided valuable environmental baseline information that helped scientists plan for subsequent sorties.

The next sortie, conducted to obtain detailed particle suspension data, also demonstrated the towing capability of the Wave Glider sub. An AMV trailed a towfish sensor module behind the submerged glider to measure turbidity. The towfish measured optical transmission to determine light attenuation and measured backscatter at three wavelengths for calculating suspended sediment and mean particle size. Having established a predredge baseline, the AMVs were deployed again to measure suspended sediment during the dredging operation. The third sortie allowed scientists to compare data obtained by towfish sensors during the second sortie with data obtained from a different optical sensor to track suspended sediment and particle size distribution. This comparison of results from state-of-the-art sensors helped the operator determine the best...
sensor system for future deployments. A final survey will be conducted after dredging is complete. These time-lapse surveys will enable scientists to compare profiles before, during and after dredging to evaluate any short- or long-term impacts on the environment.

The AMV has also helped geophysicists design seismic surveys. Seismic vessels employ several acoustic streamers, towed in parallel, to acquire geophysical data. These streamers, thousands of meters long, do not always follow directly in line behind the seismic vessel; instead, they drift laterally in response to the tides and currents they encounter. Although the streamers are steerable, this feathering can produce gaps in data coverage over an area and force the seismic vessel to steam back over that area to reacquire and infill missing data. To counter the effects of tide and current, survey planners often orient surveys in line with the direction of the predominant current.

Streamer feathering becomes a bigger problem when surveying close to fixed objects such as buoys, drilling rigs or production platforms. In support of a WesternGeco seismic vessel operating in the Gulf of Mexico, three Wave Glider sensor vehicles were deployed to report real-time weather and current data in the vicinity of rigs and platforms in the survey area. Each AMV used an acoustic Doppler...
Current profiler (ADCP) to measure current speed and direction. The data were sent via secure Internet service to the party chief aboard the seismic vessel *WG Columbus* (left). This information helped the seismic survey party chief determine how closely the vessel could pass obstructions while avoiding streamer entanglement.18

In a similar case, Total used ADCPs to aid in designing seismic surveys offshore Uruguay. There, geophysicists sought to survey an area near the confluence of two ocean currents. To adapt the acquisition to the prevailing currents on a day-to-day basis and hence to increase operational security, Total deployed a Wave Glider AMV to measure current strength. The data were transmitted in real time via satellite as the survey was underway.

Wave Glider AMVs can also provide a persistent platform to facilitate communication with subsea sensors and equipment via acoustic modem, either for operational control or to assess subsea assets (below left). Shell has used Wave Glider acoustic modems in benchmark tests to harvest data from subsea pressure monitoring transponders in the Gulf of Mexico. In most cases, such data can be recorded, transferred via satellite and analyzed anywhere in the world.

Beyond the Oil Field

Events of the past decade highlight the devastation visited upon coastal communities as a result of offshore earthquakes or major storms. To warn communities of impending danger, scientists need relevant data on a real-time basis. In the case of tsunamis, sensors deployed on buoys can help locate the epicenter of an earthquake and measure the magnitude of seafloor displacement. An array of ocean data buoys has been set up to monitor such data. The US National Oceanic and Atmospheric Administration (NOAA) monitors data from the DART (Deep-ocean Assessment and Reporting of Tsunamis) network, established to detect tsunamis and acquire data for real-time forecasts. NOAA currently has 39 DART monitoring stations in its network, and stations from other nations contribute data as well. Each DART station consists of a seafloor bottom pressure recorder (BPR) with a surface buoy anchored next to it. An acoustic link transmits data and commands between the buoy and the BPR, which collects pressure and temperature readings at 15-s intervals. The data are relayed from BPR to buoy, then transmitted by communications satellite to tsunami warning centers around the world.19
NOAA scientists recognized that there would be operational challenges in maintaining some of the DART stations following their deployment. When a station experiences a failure, the cost of mobilizing a vessel to effect repairs can strain the program’s budget. To augment the network, NOAA has deployed a Wave Glider AMV with a low-frequency acoustic modem to obtain real-time tsunami observations. This unmanned mobile tsunami meter serves as a communications gateway for transmitting live seismic data from the seafloor to the ocean surface then relaying the data to shore via satellite (above). The AMV, which also collects real-time meteorological information, can be programmed to travel to select locations or return to shore on command.

Accurate storm forecasting is also critical to protecting lives and assets of coastal communities. Having developed tools to predict the general track a storm might take, NOAA now seeks to improve predictions of storm intensity. Along the US gulf and east coasts, the greatest threats come from hurricanes. In an effort to better understand how hurricanes gain or lose strength, NOAA is targeting the sea/air interface, where warm ocean waters transfer heat energy to the overlying storm system. Weather experts believe that temperatures beneath the ocean’s surface may contribute significantly to this energy exchange as storm winds and waves churn the waters below the surface.

However, extracting data from the center of a hurricane can be difficult. Storm-chaser aircraft fly into these violent weather systems at several thousand feet above the ocean. They probe the storm using radar to gauge conditions at the ocean surface or they drop sensors from the plane to obtain a detailed vertical profile of atmospheric conditions inside the storm. Satellites observe surface temperatures from hundreds or thousands of miles above the ocean, but these measurements may be obscured by cloud cover, and they provide no information on the heat exchanged in storm-churned waters beneath the surface. Furthermore, they need to be compared with ground truth measurements obtained in the actual storm environment. Such measurements can be gathered only by venturing into the storm itself.

These environments are too turbulent for manned weather vessels or research aircraft, so NOAA scientists are testing unmanned mobile sensor platforms to observe this energy transfer. NOAA has used the Wave Glider AMV in the Atlantic Ocean to collect critical data in areas that would be too difficult or too dangerous to access by other means. Monitoring an area north of Puerto Rico, the sensor platform is equipped with a standard weather station to measure temperature, humidity, barometric pressure and wind speed, direction and gusts. It also has a directional wave sensor and a thermistor chain to measure the water temperature from the surface down to 7 m [23 ft] in depth. This sensor platform demonstrated that high-quality temperature measurements from the upper ocean can be collected.
by autonomous vehicles in a harsh environment and telemetered in real time. An AMV also allows scientists to gather data from various locations as the vehicle roves through the storm.

**Wave of the Future**

Having traveled 14 months and 14,800 km [9,200 mi] across the Pacific Ocean, the Wave Glider AMV has gained a record of reliability. This autonomous sensor platform has proved capable of carrying out a variety of important ocean monitoring functions formerly assigned to manned vessels—but over a longer time frame and at lower cost than traditional methods. Furthermore, its station keeping ability lets the AMV duplicate the persistence and measurement functions of a moored ocean-monitoring buoy. In this mode, it significantly reduces the expense, time and risk incurred by ships and crews to deploy, recover and maintain a traditional network of buoys. Its compact size also permits great flexibility and adaptability for rapid deployment to unforeseen or fast-changing events to monitor conditions on, above or below the ocean’s surface.\(^2^1\)

As offshore exploration and production move into deeper and more remote areas of the world’s oceans, the drilling rigs, production platforms, vessels and pipelines used in these operations will increasingly rely on autonomous vehicles for support. The capability to operate at or below the sea/air interface will serve the AMV customer in providing communication relays between surface and subsurface installations.

\(^{21}\) Leroy and Hine, reference 8.

\(^{22}\) Leroy and Hine, reference 8.

A new generation of larger, purpose-built Wave Glider vehicles will support subsurface well installations and field operations. The SV3 model will be more than 35% longer than previous models and will carry a larger payload. Future systems may be able to generate electricity from wave motion and may also include auxiliary electric propulsion to enhance maneuvering and collision avoidance capabilities (above).\(^{22}\) The next generation of Wave Glider autonomous vehicles will be instrumental in extending the frontiers of exploration and production.  

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^ Wave of the future. The current Wave Glider SV3 prototype features an electric propulsion system with a low-drag propeller (black cone beneath the vertical fin). This larger model will accommodate a payload of 45 kg [100 lbm].