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ANTISUBMARINE WARFARE

The Wave Glider, an Energy-Harvesting Autonomous Surface Vessel

Persistent Presence Enables Acoustic Operations As a Virtual Buoy or Mobile Platform

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The Wave Glider is a new wave-propelled, persistent ocean vehicle. Roger Hine, the lead inventor of the vehicle and the chief executive officer of Liquid Robotics Inc., began work on the vehicle in 2005 with a vision to enable new types of ocean observation that would not require costly deepwater moorings or ship operations. The key innovation of the Wave Glider is its ability to harvest the abundant energy of ocean waves to provide essentially limitless propulsion.

Glider Design

The Wave Glider is a hybrid sea surface and underwater vehicle comprised of a submerged glider attached via a tether to a surface float. The glider is propelled by the conversion of ocean wave energy into forward thrust, independent of wave direction. The wave energy propulsion system is purely mechanical; no electrical power is generated by the propulsion mechanism. Just as an airplane's forward motion through the air allows its wings to create an upward lifting force, the submerged glider's vertical motion through the comparatively still waters at the glider's depth allows its wings to convert a portion of this upward motion into a forward propulsion force. As waves pass by on the surface, the submerged glider acts as a tug, pulling the surface float along a predetermined course. The separation of the glider from the float is a crucial aspect of the vehicle design.

Power for Additional Systems

While wave energy provides propulsion, the Wave Glider carries 665 watt-hours of rechargeable lithium-ion batteries to supply the energy needs of its navigation, control, communications and payload systems. This battery subsystem is composed of seven smart battery packs that are electrically isolated from each other. Only two batteries are in use at any given time, and each battery has separate discharging and monitoring circuitry. The Wave Glider's navigation, control and communications systems require on average only 0.7 watts of continuous power.

To achieve the Wave Glider's long-duration missions, the battery energy consumed by the command, control, communications and payloads systems must be continuously replenished.

Thus, the Wave Glider carries two photovoltaic solar panels, each rated to deliver up to 43 watts of peak power. In practice, however, the average continuous power delivered by the solar panels is substantially less than the combined 86 watts of peak output power. Mission latitude and the season of the year have a significant effect on the power generated by the vehicle's solar panels.

The Wave Glider is a two-part, wave-propelled, persistent ocean vehicle.

There are also several other factors that influence the overall average continuous power produced by the solar panels, including light level, temperature, shading, fouling, and conversion and storage efficiencies. When taken together, these factors reduce the average continuous power available to payloads to approximately 10 watts. While

just a few watts is sufficient for many payloads—such as cameras and passive receivers—additional development effort will be required to increase available payload power to realize the full potential of the Wave Glider platform, particularly when operating in higher latitudes. Liquid Robotics is exploring concepts to harvest wave energy on a small scale to meet these needs.

Navigation and Control

The Wave Glider relies on a 12-channel global positioning system receiver as its primary navigation sensor and also carries a tilt-compensated magnetic compass with three-axis accelerometers. Some newer vehicles also carry a water speed sensor, allowing for short-term dead reckoning. The Wave Glider's typical navigation accuracy is better than three meters, and it navigates autonomously to achieve waypoints and to keep station.

The Wave Gliders are controlled via a simple Web-based command and control interface. Each Wave Glider vehicle communicates with the shore-based Web server by initiating an Iridium (Bethesda, Maryland) modem messaging session, which is then received at an Iridium network ground station where the data is redirected onto the Internet. These sessions occur at configurable intervals, typically every five and 15 minutes.

Using the Web-based interface, any number of operators (with the appropriate authorizations) can control any Wave Glider vehicle from any Internet-enabled computer or cell phone. Similarly, subscribers can monitor vehicle status and data on an as-needed basis.

The vehicles also carry short-range, high-bandwidth radio modems and acoustic modems for subsea telemetry.

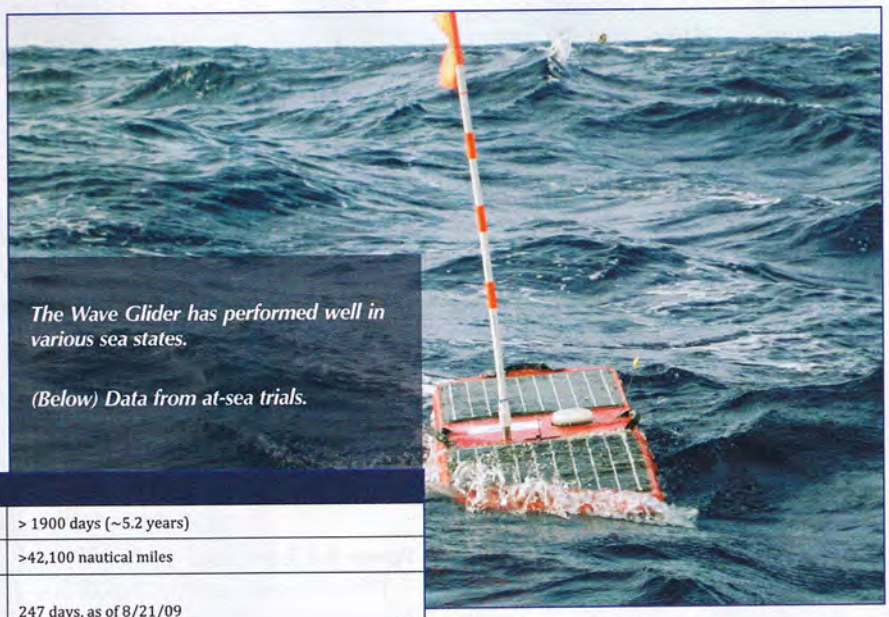
Performance in Sea Trials

Over the past two and half years, the technology has undergone several sea trials, driving prototype and product-level vehicle development programs. The current production generation of the Wave Glider is the beneficiary of more than five years of combined sea time and more than 42,000 cumulative nautical miles of missions.

Liquid Robotics, with U.S. Coast Guard permission, maintains a test range in a one-square-mile area offshore Puako, Hawaii, and all initial engineering trials and operational/acceptance testing are conducted inside the Puako test range. Wave Gliders have also demonstrated their effectiveness in a wider range of sea conditions in trials conducted farther offshore.

The Wave Glider vehicle Red Flash circumnavigated Hawaii's Big Island on January 9 through 18, a 343-nautical-mile mission that it completed in nine days and two hours with an average speed over ground of 1.57 knots. Sea conditions during this mission were estimated to be 10-foot seas and 15-knot winds. A similar engineering trial and demonstration was conducted in August along the U.S. West Coast, from Monterey Bay to the southern maritime border of the United States. This mission lasted 11 days and two hours and covered 403 nautical miles, for an average speed over ground of 1.53 knots. Additional long-term missions are currently under way, including multi-month, basin-scale ocean transits.

Finally, as an engineering endurance trial, one Wave Glider is conducting a station-keeping mission in the Puako test range, augmented with frequent transits out into the open ocean. So far, this Wave Glider has accumulated more than 6,200 nautical miles and nine months of continuous operation. The goal of this mission is to demonstrate more than a full year of continuous operation.



The Wave Glider has performed well in various sea states.

(Below) Data from at-sea trials.

Wave Glider Testing Milestones and Statistics	
Cumulative Mission Time	> 1900 days (~5.2 years)
Cumulative Mission Miles	>42,100 nautical miles
Longest Single Mission Endurance (so far)	247 days, as of 8/21/09
Longest Single Mission Distance (so far)	2150 nautical miles, as of 8/21/09
Cumulative Miles on a Single Vehicle (so far)	6200 nautical miles, as of 8/21/09
Max. Sustained Sea State for Vehicle Operations	SS6: 15+ foot seas, 40+ knot winds

The Wave Glider vehicle has been designed to withstand extreme seas. Ultimately, the glider's endurance is limited only by its robustness, as its propulsion power is effectively unlimited. In Hurricane Flossie in 2007, the Wave Glider demonstrated an ability to weather more than 10-foot seas and winds of more than 40 knots.

But the opposite extreme, very calm seas, presents a greater challenge to the successful conduct of the Wave Glider's mission. Without wave energy to harvest, the Wave Glider would not be able to maintain course and may not be able to keep station. Thankfully, the ocean is rarely calm, and even when it is, it rarely remains so for long. Wave Gliders have been designed to make significant headway even in very mild seas (i.e., with wave heights of a few inches or less). Even in these extremely calm conditions, the vehicle is able to

maintain a forward speed of 0.25 to 0.50 knots. This speed is sufficient to allow the vehicle to keep station against typical surface currents.

Modular Payloads

The Wave Glider has modular mechanical, electrical and software interfaces to accept a wide variety of payloads. All command and control, communications, and navigational electronics are contained in a core electronics module, which also houses the batteries and their charging electronics. Dedicated forward and aft payload modules house most payload sensor systems and support electronics.

Several payload modules have been demonstrated on the Wave Glider, including passive hydrophones and towed hydrophone arrays, marine weather stations, still and video cameras, and acoustic Doppler current profilers. The current generation of the Wave Glider has also towed an instrumented buoy that was itself towing an acoustic modem at the end of a long cable. More recently, an acoustic modem and its support electronics have been integrated onto the Wave Glider float, eliminating the need to tow the hydrophone payload.

Acoustic Monitoring of Marine Life

Liquid Robotics is collaborating with the Scripps Institution of Oceanography (SIO) to integrate their high-frequency acoustic recording package (HARP) onto a Wave Glider. The HARP was designed for long-term (up to one year) deployment as an autonomous, bottom-mounted sensor for broadband marine mammal monitoring. The HARP system consists of an acoustic sensor, signal preconditioning and sampling electronics, and a large data storage system (currently two terabytes). Several HARP systems are currently in use worldwide to acoustically monitor marine mammals for long-term behavioral and ecological studies.

Recently, SIO has repackaged the HARP electronics into one of the Wave Glider's modular payload housings. The HARP hydrophone will be towed behind the Wave Glider on a short cable. The Wave Glider's persistence and nearly silent wave-powered propulsion make it an ideal host platform for the HARP and other acoustic sensor payloads. The Wave Glider HARP payload will provide two months of continuous acoustic recording in a wide band from 10 hertz to 100 kilohertz. Missions of one year or longer are possible using the scheduled or acoustically triggered recording modes. Short snippets of data—for quality control and for transient event reporting—will be transmitted to shore via the Wave Glider's Iridium satellite communications link. Long-term broadband ocean acoustic recordings from the Wave Glider HARP system can provide detailed information on a variety of sources, including natural sounds (from baleen and toothed whales and other marine animals like pinnipeds, sirenians and fish and weather phenomena like wind, rain and earthquakes) and from anthropogenic sources (such as ships, sonars and seismic exploration).

Engineering sea trials with the Wave Glider HARP system began in October. These trials will validate all aspects of the integration of the payload with the Wave Glider platform, including platform acoustic self-noise measurements. Following successful completion of these trials, the Wave Glider HARP system will likely be deployed for a variety of operational missions, such as observing the migratory behavior of cetaceans along the California coast, monitoring the presence and activities of marine mammals in the vicinity of naval training exercises, or long-term monitoring of submerged vessel traffic in sensitive areas.

References

A complete list of references may be obtained by contacting the authors at justin.manley@liquidr.com. ■

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