The Wave Glider: A Wave-Powered Autonomous Marine Vehicle

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***Abstract* - The Wave Glider is a new autonomous marine vehicle that is unique in its ability to harness ocean wave energy for platform propulsion. This paper provides an overview of the Wave Glider vehicle's architecture and capabilities, and presents results from the extensive engineering sea trials that we have conducted with several prototype and the current production generations of the vehicle. The vehicle's performance in a variety of ocean conditions is described. The vehicle's robustness and capabilities for extended mission durations are also examined. The vehicle's autonomous control architecture is explained, as are the web-based interfaces for external control and monitoring of the platform. Finally, we discuss several payload packages that have been or are currently being developed for the vehicle.**

I. INTRODUCTION

The Wave Glider is a new class of wave-propelled, persistent ocean vehicle, Fig. 1. Roger Hine, the lead inventor of the vehicle and the CEO of Liquid Robotics, began work on the Wave Glider vehicle in 2005 with a vision to enable new types of ocean observation that did not require costly deep-water moorings or ship operations. Encouraged by immediate success with initial prototype designs, Mr. Hine and several colleagues founded Liquid Robotics, Inc. in 2007 to further develop the platform for scientific, commercial, and military applications. The key innovation of the Wave Glider is its ability to harvest the abundant energy in ocean waves to provide essentially limitless propulsion. Two solar panels continually replenish the batteries that are used to power the vehicle's control electronics, communications systems, and payloads. Table I gives an overview of the characteristics,

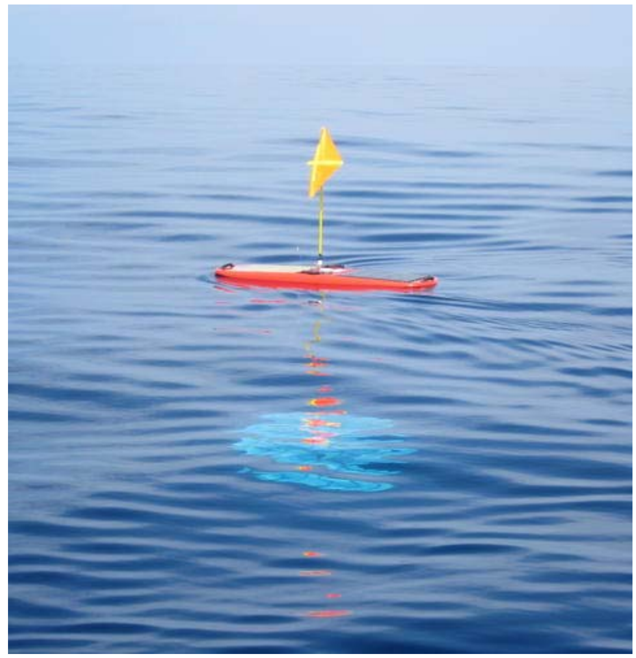


Fig. 1 The Wave Glider is a two-part vehicle, consisting of a surface float connected to a submerged glider via a flexible tether. The Wave Glider harnesses wave energy for propulsion, decoupling platform endurance from battery or chemical energy storage systems. The Wave Glider is able to maintain headway on its desired course in calm seas and independent of wave direction.

TABLE I
CHARACTERISTICS AND CAPABILITIES OF THE WAVE GLIDER VEHICLE

Physical Characteristics	
Vehicle Configuration	Submerged glider connected to a surface float by a tether.
Dimensions	Float: 2.1m x 0.6m; Glider: 0.4m x 1.9m; Wings: 1.1m wide
Weight and Buoyancy	75 kg mass, 150 kg displacement
Endurance	Up to 1 year
Capabilities and Functionality	
Propulsion Power	Mechanical conversion of wave energy into forward propulsion.
Speed through Water	>0.5 kt in Sea State 1 (SS1); >1.5 kt in Sea State 3 (SS3).
Battery	86W (peak) solar panel charging a 665 Wh Li-ion battery pack.
Payload Power Available	10 W continuous (typical), depending upon latitude, weather, etc.
Communications Systems	Iridium Satellite Modem. RF Modem
Navigation Systems	12 Channel, WAAS enabled GPS; Compass; Water Speed (Optional)
Control Interfaces	Web-based, GUI Chart interface, with location and status indicators.
Proven Survivability	SS6 (WMO) (14-18ft seas, 30-40kt winds)
Emergency Location Devices	Light and RF beacon. Optional acoustic beacon.

capabilities, and features of the first production generation of the Wave Glider vehicle.

A. Platform Architecture and Principle of Operation

Wave Glider is a hybrid sea-surface and underwater vehicle in that it is comprised of a submerged "glider" that is attached via a tether to a surface float. The Wave Glider vehicle is propelled by the conversion of ocean wave energy into forward thrust, independent of wave direction, Fig. 2. 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 a tug pulling the surface float along a predetermined course. Separation of the glider from the float is a crucial aspect of the vehicle design. Engineering prototypes and the first product generation of the Wave Glider vehicles have logged a combined total of more than 42,000 nautical miles at sea, with the longest continuous mission lasting 247 days as of August 21, 2009.

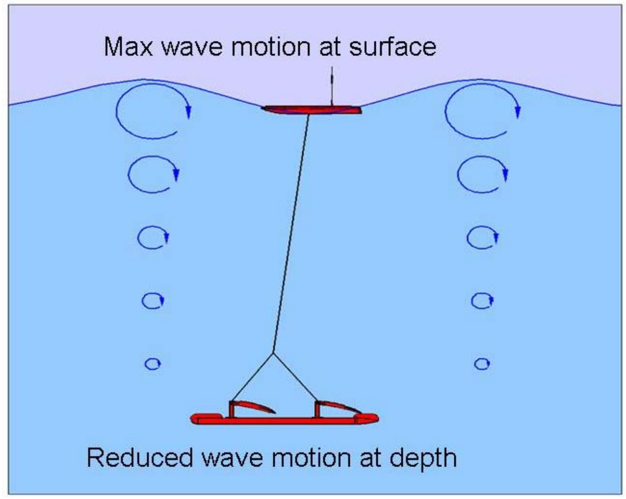


Fig. 2 Surface waves pull the submerged glider up from below as a wave crest passes the float. The glider's wings convert a portion of this wave-powered vertical forcing into forward motion. The magnitude of the glider's forward propulsive force is proportional to the difference between the ocean wave amplitudes at the surface and at the glider.

II. PROPULSION PERFORMANCE AND ENDURANCE

There is substantial power available in ocean waves, and the Wave Glider harnesses this power to maintain an average forward speed of 1.5 kts in typical seas with one to three foot waves. The Wave Glider's forward speed is dependent upon the amplitude of the surface waves, the overall buoyancy force provided by the float, and the glider's weight, Table II. The Wave Glider's mass and buoyancy and the length of its tether have been tuned to provide excellent wave-energy propulsion performance in both energetic and calm seas alike.

TABLE II

TO FIRST ORDER, WAVE GLIDER FORWARD SPEED IS A FUNCTION OF SEA STATE. WAVE GLIDER'S AVERAGE SPEED FOR LONG MISSIONS THAT EXPERIENCE A VARIETY OF SEA CONDITIONS IS 1.5 KTS.

Wave Glider Propulsion Speed Performance	
Flat Calm	0 kts
Sea State 0	0.25 to 0.50 kts
Sea State 1	0.50 to 1.50 kts
Sea State 2	1.25 to 2.00 kts
Sea State 3+	1.50 to 2.25 kts
Long Mission Average	1.50 kts

A. High Sea State

The Wave Glider vehicle has been designed to withstand extreme seas. Ultimately, the Wave 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 10+ foot seas and 40+ kt winds (Sea State 5), Fig. 3. More recently, the Wave Glider "Red Flash" while surveying along the California coast. Besides the engineered robustness of its component pieces, Wave Glider also exhibits a natural "sea anchor" behavior that helps it weather unusually strong weather. As the sea surface becomes increasingly energetic, the Wave Glider tends to "dig in" to the waves. The buoyancy force of the float is overcome by the vertical drag motion of the submerged glider causing the surface float to dive through the middle of larger waves. This behavior acts as a natural governor to limit the maximum forces imposed on the vehicle. Future designs could accentuate this effect by strengthening the wings and providing a mechanism to lock the wing angle in the horizontal (maximum) drag position. In short, the Wave Glider has already demonstrated admirable robustness in strong seas over long endurance deployments of over eight months.

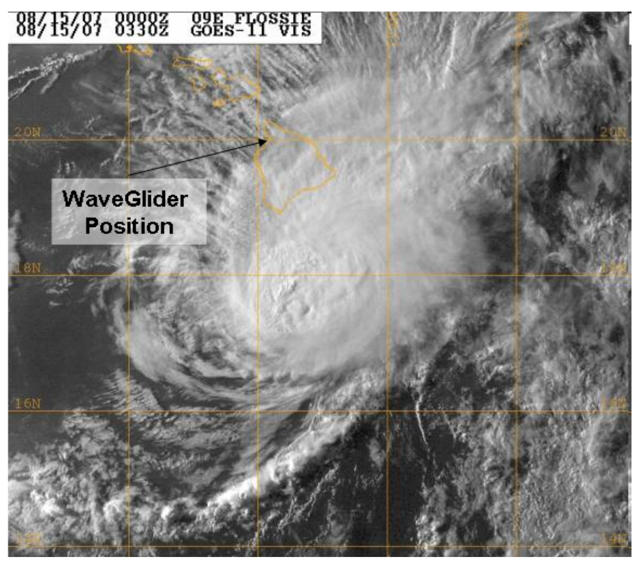


Fig. 3 A Wave Glider holds position in 10 ft seas and 40 kt winds as the remnant of Hurricane Flossie passes within 100 miles of the southern tip of the Big Island of Hawaii on August 14, 2007.

B. Low Sea State

The opposite extreme of very calm seas represents 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 so calm, and when it is it rarely remains calm for long. As is illustrated in Fig. 4, the Wave Glider has been designed to be capable of making 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 Wave Glider is able to maintain a forward speed of 0.25 to 0.50 kts. This speed is typically sufficient to allow the vehicle to keep station against typical surface currents.

III. Platform Capabilities

A. Batteries and Solar Power

Wave Glider carries 665 Wh 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 only 0.7 W of (averaged) continuous power. The longest Wave Glider mission duration without a battery recharge (i.e., without the benefit of the solar panels) is about 23 days. This duration would decrease further if more payload sensors are added.

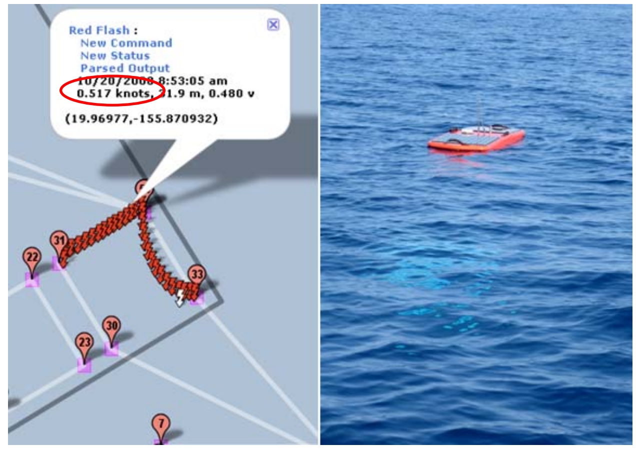
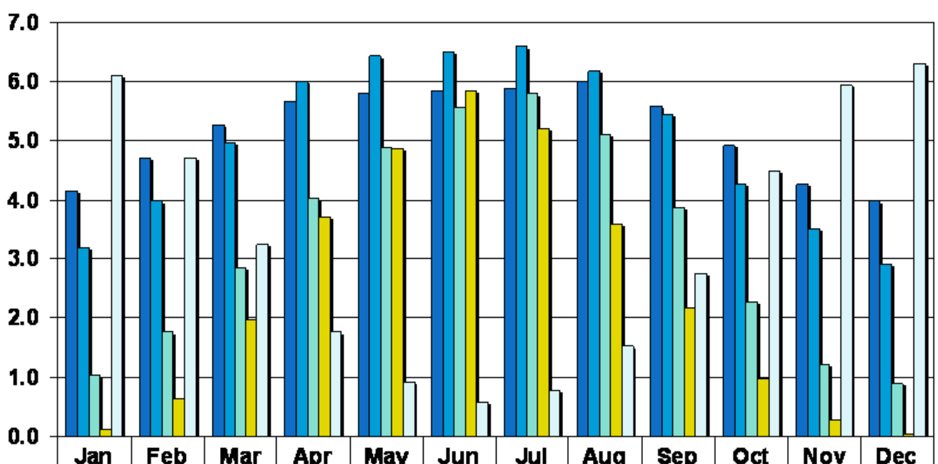


Fig. 4 The Wave Glider typically maintains forward speed of 0.25 to 0.50 kts in calm seas. The left image is a screen capture of the Liquid Robotics' web-based mission monitoring and control interface, showing mission way points and vehicle trajectory for the Wave Glider "Red Flash" when operating in calm seas, right.

To achieve the Wave Glider's promise for long duration missions, the battery energy consumed by command, control, communications, and payloads systems must be continuously replenished. To meet this need, the Wave Glider carries two photovoltaic solar panels that are each rated to deliver up to 43 W of peak power. In practice, though, 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. These factors determine the number of hours of day light and the angle of incidence at which solar rays impinge upon the PV panels. Other factors such as cloud cover also have significant effects on the average power delivered by the solar panels. Fig. 5 illustrates the variability of total incident solar power in kWh/m^2/day as a function of the location and time of the year (and using average climatology for each location). Low latitude regions – such as at Liquid Robotic's marine operations center in Puako, Hawaii – maintain high total incident solar energy averages throughout the year. Higher latitude regions – such as Nome, AK and Punta Arenas, Chile – experience both high peaks in their summer months and low minimums during winter months. There are also several other factors that influence the overall average continuous power produced by the PV panels including light level, temperature, shading, fouling, and conversion and storage efficiencies. When taken together, these factors significantly reduce the (averaged) continuous power available to payloads to approximately ten (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 (2 to 20 W) to meet these needs. As is shown in Fig. 6, the average power available in surface



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Puako, HI	4.2	4.7	5.3	5.7	5.8	5.8	5.9	6.0	5.6	4.9	4.3	4.0
San Diego, CA	3.2	4.0	5.0	6.0	6.4	6.5	6.6	6.2	5.4	4.3	3.5	2.9
Seattle, WA	1.0	1.8	2.9	4.0	4.9	5.6	5.8	5.1	3.9	2.3	1.2	0.9
Nome, AK	0.1	0.6	2.0	3.7	4.9	5.8	5.2	3.6	2.2	1.0	0.3	0.1
Punta Arenas, CHL	6.1	4.7	3.2	1.8	0.9	0.6	0.8	1.5	2.8	4.5	5.9	6.3

Fig. 5 Solar energy incident on a horizontal surface in kWh/m2/day. Latitude, angle of incidence, and seasonal weather all affect the average solar energy. (data from www.nrel.gov/gis/solar.html)

waves is substantial, even for small and longer period waves. Alternatively, larger PV panels could be installed on the Wave Glider by increasing the size of the surface expression.

B. Navigation and Station Keeping

The Wave Glider relies upon a 12-channel GPS 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 3 meters, CEP50 (circular error probable, 50% confidence).

The Wave Glider navigates autonomously to achieve waypoints and to keep station. It has demonstrated the ability to hold station in the open ocean or the littorals for long durations with a watch circle of only 25 meters, CEP50, Fig.. This is in sharp contrast with deep-ocean moorings where watch circle widths are typically on the order of ocean depth.

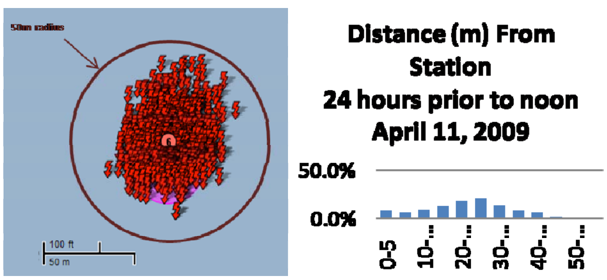


Fig. 7 Wave Glider acts as a virtual buoy, maintaining a tight watch circle of 25m, CEP50, under typical sea state conditions. Furthermore, the radius of the watch circle radius is independent of depth, allowing the Wave Glider to hold position above instruments on the ocean floor with much higher precision than traditional moored systems.

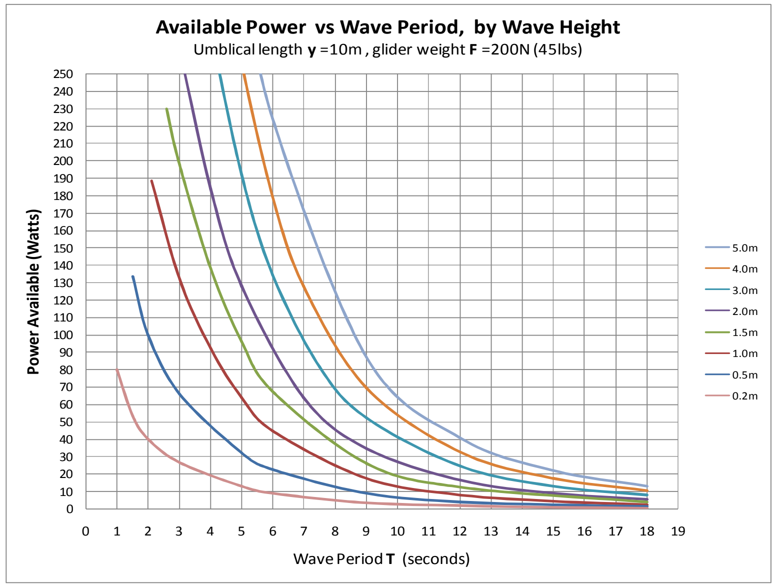


Fig. 6 Wave power as a function of wave period and wave height for a 33 ft tether and a 45 lb glider.

C. Communication, Command, and Control

The Wave Glider's communication and control architecture is shown in Fig. 7. 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 modem messaging session which is 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 command and control interface, any number of operators (with the appropriate authorizations) can control any Wave Glider vehicle from any Internet-enabled computer, PDA, or cell-phone. Similarly, subscribers can monitor vehicle status and data on an as needed basis.

Wave Glider vehicles also carry short-range, high-bandwidth radio modems that are used primarily to communicate with surface support vessels during near-shore engineering trials. RF modems give a faster update rate for vehicle command and control and allow a larger amount of vehicle status or payload data to be offloaded from the vehicle. Finally, an acoustic communications modem has been carried by a Wave Glider in an experimental

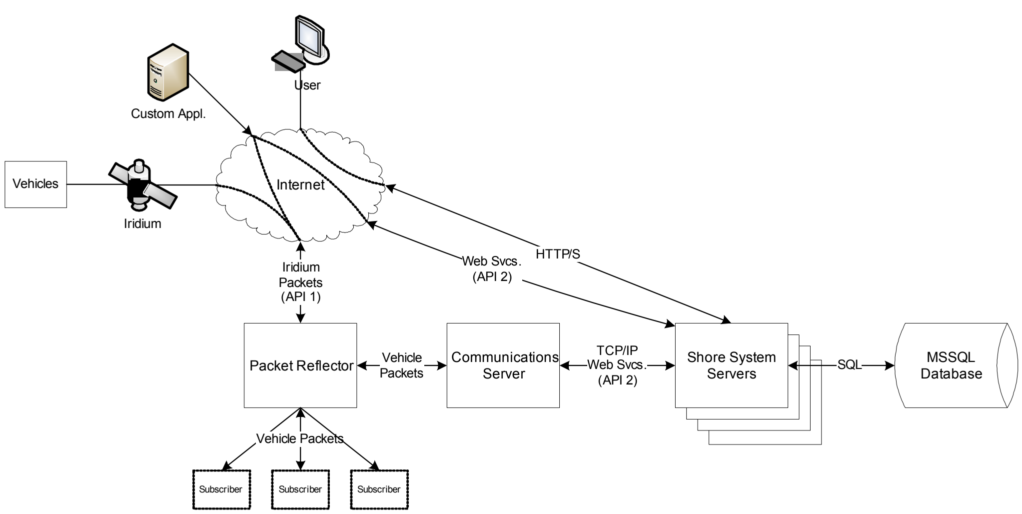


Fig. 4 Wave Glider Communications and Control scheme. An Iridium satcomm link serves as the command and control channel for deployed vehicles. A web interface to a dedicated Wave Glider communications server allows multiple operators to control the vehicle and for multiple subscribers to receive Wave Glider data.

application.

Fig. 9 shows the Wave Glider command and control interface. This web-based tool allows operators to issue commands to and monitor status from several vehicles from a single application. An account-based credentialing scheme allows an operator to interact with deployed systems from any available computer, including cellular phones that support web browsing.

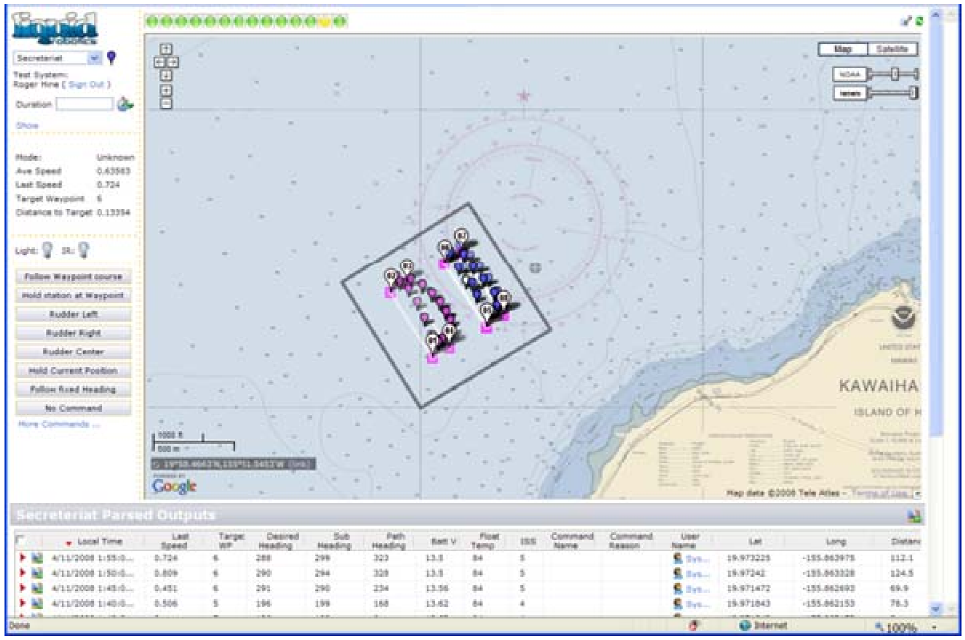


Fig. 9 Wave Gliders are monitored and controlled from via a simple web-based interface.

D. Payloads

The Wave Glider has modular mechanical, electrical, and software interfaces to accept a wide variety of payloads modules, Fig. 10. All command and control, communi-cations, and navigations 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 cameras, and video cameras, and acoustic Doppler current profilers (ADCPs). The current generation of the Wave Glider has more recently demonstrated towing an instrumented buoy that was itself towing an acoustic modem at the end of a long cable. More recently, the acoustic modem payload and its support electronics have been integrated onto the Wave Glider float. Future planned payloads include hydrographic sensors, such as conductivity, temperature, and depth (CTD) sensors and single beam sub-bottom profiling sonars.

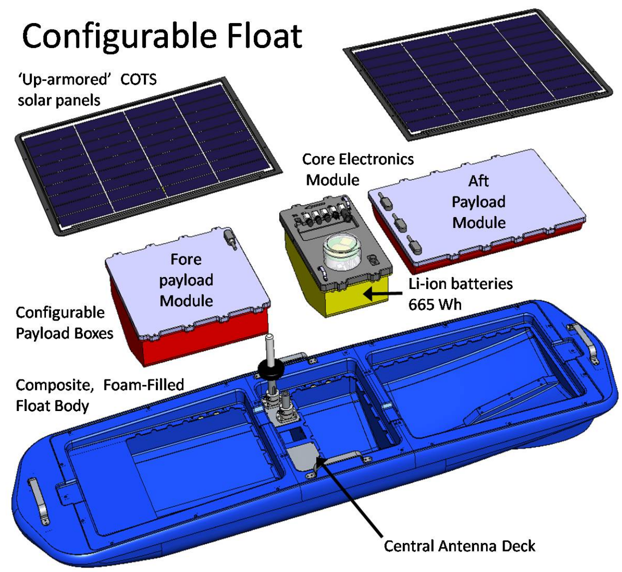


Fig. 10 The Wave Glider float is highly modular, with two dedicated modular "dry-boxes" for easy integration of payloads.

In collaboration with the NOAA Pacific Marine Environmental Laboratory (PMEL), we are working to integrate a carbon dioxide partial pressure and sea water pH sensor package into the Wave Glider platform. A description of the development and integration of this payload onto the Wave Glider and of the important carbon science that will be conducted with a network of such vehicles is provided in a companion paper [1].

IV. Engineering Trials and Capability Demonstrations

Over the past two and half years, Liquid Robotics has pursued a vigorous course of at-sea speed performance, endurance, and sea-worthiness (i.e., robustness) trials as the primary driving force in its prototype and product-level vehicle development programs, Table III. The current production generation of the Wave Glider is the beneficiary of over five (5) years of combined sea time and over 42,000 cumulative nautical miles of missions. LRI has been granted permission by the U.S. Coast Guard to maintain a Wave Glider test range in a 1 nmi by 1 nmi area off-shore from Puako on the Big Island of Hawaii. This test range is adjacent to LRI's marine operations center in nearby Kawaihae Harbor. All initial engineering trials and operational/acceptance testing is conducted inside the Puako test range.

Table III

Wave Glider Testing Milestones and Statistics	
Cumulative Mission Time	1906 days (~5.2 years)
Cumulative Mission Miles	>42,100 nmi
Longest Single Mission Endurance (so far)	247 days, as of 8/21/09
Longest Single Mission Distance (so far)	2150 nmi, as of 8/21/09
Cumulative Miles on a Single Vehicle (so far)	6200 nmi, as of 8/21/09
Max. Sustained Sea State for Vehicle Operations	SS6: 15+ ft seas, 40+ kt winds

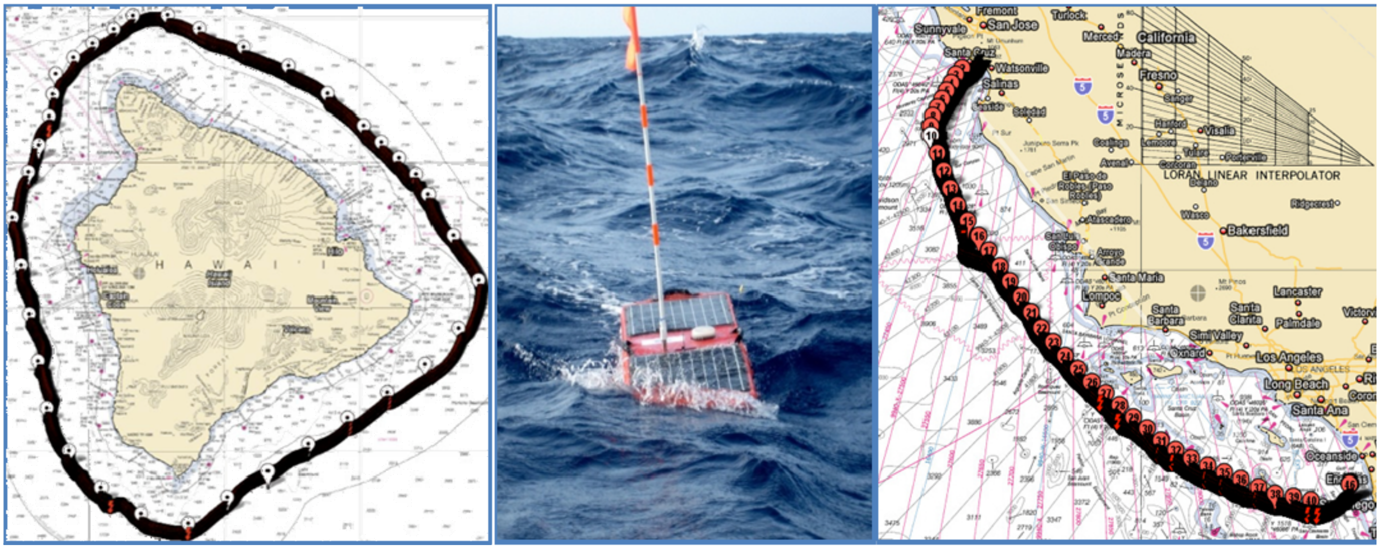


Fig. 11 Wave Glider Demonstration Trials and Missions: (Left) Circumnavigating the Big Island of Hawaii, January 9-18, 2009. (Middle) Typical Sea State 12-nmi offshore of Hawaii. (Right) Traversing California Coast, Monterey to San Diego, April 17-28, 2009.

Once initial trials have been satisfactorily completed, additional testing to expose the Wave Glider to a wider range of sea conditions is conducted farther off-shore. For example, Fig. 11 (left) shows the trajectory of the Wave Glider vehicle “Red Flash” circumnavigating the Big Island of Hawaii in international waters, January 9-18, 2009, a 343 nmi mission that the vehicle completed in 9 days, 2 hours with an average speed over ground of 1.57 kts. Sea conditions during this mission were estimated to be 10 ft seas and 15 kt winds (Ses State 5), Fig. 11 (middle). A similar engineering trial and demonstration was conducted along the California coast, from Moss Landing (Monterey Bay) to San Diego, April 17-28, 2009, Fig. 11 (right). This mission lasted 11 days, 2 hours and covered 403 nmi, for an average speed over ground of 1.53 kts. Additional long term missions are currently underway, including multi-month, basin-scale ocean transits. Finally, as an engineering endurance trial, one Wave Glider is conducting a station keeping mission in our Puako test range, augmented with frequent transits out into the open ocean. So far, this Wave Glider has accumulated over 6200 nmi and eight months of continuous operation. Our goal is to demonstrate more than a full year of continuous operation with this mission.

V. Conclusion

Through extensive engineering trials and demonstrations, the Wave Glider’s capability for long-term autonomous operation in the open and coastal oceans has been firmly established. We believe that the Wave Glider represents a significant advance for economical and persistent access to the open and coast oceans for a variety of scientific, commercial, and military applications. Several mission-specific science and military payloads have been or are currently in the process of being integrated onto the Wave Glider.

References

[1] S. Willcox, C. Meinig, C. Sabine, N. Lawrence-Slavas, T. Richardson, R. Hine, and J. Manley, “An Autonomous Mobile Platform for Underway Surface Carbon Measurements in Open-Ocean and Coastal Waters,” to appear in *Proceedings of MTS/IEEE Oceans 2009 Conference*, Biloxi, MS, Oct 26-29, 2009