

## The Wave Glider, a Unique Platform for Ocean Science

Justin Manley, Director of Scientific and Commercial Business, Liquid Robotics Inc.  
Scott Willcox, Director of Defense Business and Principal Technologist, Liquid Robotics Inc.  
Palo Alto, California - United States of America

### The Wave Glider, an energy harvesting unmanned surface vehicle

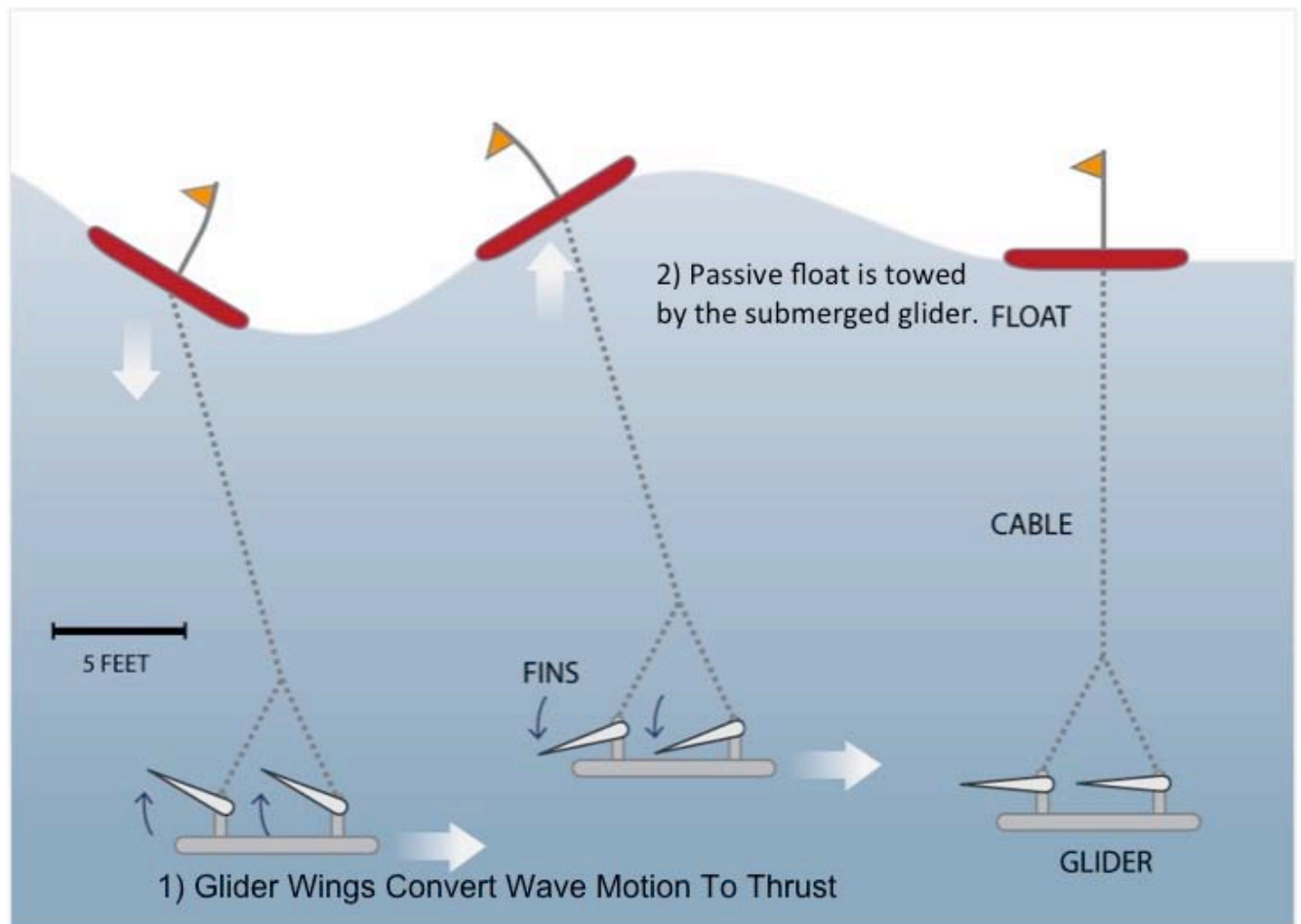
The Wave Glider, Figure 1, is a unique wave-propelled, unmanned, persistent ocean vehicle. Development of the Wave Glider vehicle began in 2005 with a goal to enable new ocean observations independent of costly deep-water moorings or ship operations. Encouraged by immediate success with initial prototype designs, Liquid Robotics, Inc. was founded in 2007 to further develop the technology for scientific, commercial, and military applications. The key innovation of the Wave Glider is its ability to harvest energy from ocean waves to provide essentially limitless propulsion and ensuing persistent presence at the air-sea interface.



Figure 1: The Wave Glider at sea

Wave Glider is a two-body sea-surface and underwater vehicle comprised of a submerged “glider” attached via a tether to a surface float. The system is propelled by the conversion of ocean wave energy into forward thrust, independent of wave direction. The wave energy propulsion mechanism is purely mechanical; no electrical power is generated. 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 calm waters at the glider’s depth allows its wings to convert a portion of the upward motion into a forward force. As waves pass on the surface, the submerged glider acts a tug pulling the surface float along a desired

course, controlled by a rudder on the glider. Separation of the glider from the float is a crucial aspect of the vehicle design. Figure 2 illustrates the principles of Wave Glider propulsion.



**Figure 2: Principles of Wave Glider Propulsion**

There is substantial power available in ocean waves, and the Wave Glider harnesses this power to maintain an average forward speed of 1.5 knots in typical seas with one to three foot waves. The Wave Glider's speed is dependent upon the amplitude of the surface waves, the buoyancy force provided by the float, and the glider's weight. Sea State 0 has been observed to yield speeds of 0.25 to 0.5 knots while Sea State 3 and higher can result in speeds of over 2.0 knots. 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.

While wave energy provides propulsion, navigation, control, communications, and payload systems demand electrical power. Therefore, Wave Glider carries 665 Watt hours of rechargeable lithium-ion batteries. This battery subsystem consists of seven smart battery packs electrically isolated from each other. Only two batteries are in use at any given time and each battery has independent discharging and monitoring circuitry. The Wave Glider's navigation, control, and communications systems require only 0.7 Watts of (averaged) continuous power. The longest Wave Glider mission duration without a battery recharge (i.e., without the benefit of the solar panels) is on the order of three weeks days. This duration would decrease further with more payload sensors aboard.

To achieve the Wave Glider's promise for long duration missions, the battery energy consumed by onboard systems must be replenished. Thus the Wave Glider carries two photovoltaic solar panels, each rated to deliver 43 Watts of peak power. In practice, the average continuous power delivered by the solar panels is less than the combined 86 Watts of peak output power. Mission latitude and the season of the year impact the power

generated by the vehicle's solar panels. Local factors that influence the average continuous power produced by the solar panels include light level, temperature, shading, fouling, and conversion and storage efficiencies. When taken together, these factors reduce the (averaged) continuous power available to payloads to approximately ten Watts. While just a few Watts is sufficient for many payloads – such as cameras and physical oceanographic sensors – additional development effort is underway to increase available payload power. This will enable 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, for conversion to electric power to meet these needs.

The Wave Glider employs a 12-channel GPS receiver as its primary navigation sensor and carries a tilt-compensated magnetic compass with three-axis accelerometers. Some 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. The Wave Glider navigates autonomously to reach waypoints and to keep station.

Wave Gliders are controlled via a simple web-based command and control interface, Figure 3. Each vehicle communicates with a 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 to 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 from Internet-enabled computers or smartphones. Similarly, subscribers can monitor vehicle status and data as needed. Wave Gliders can also carry short-range, high-bandwidth radio modems and acoustic modems for subsea telemetry.

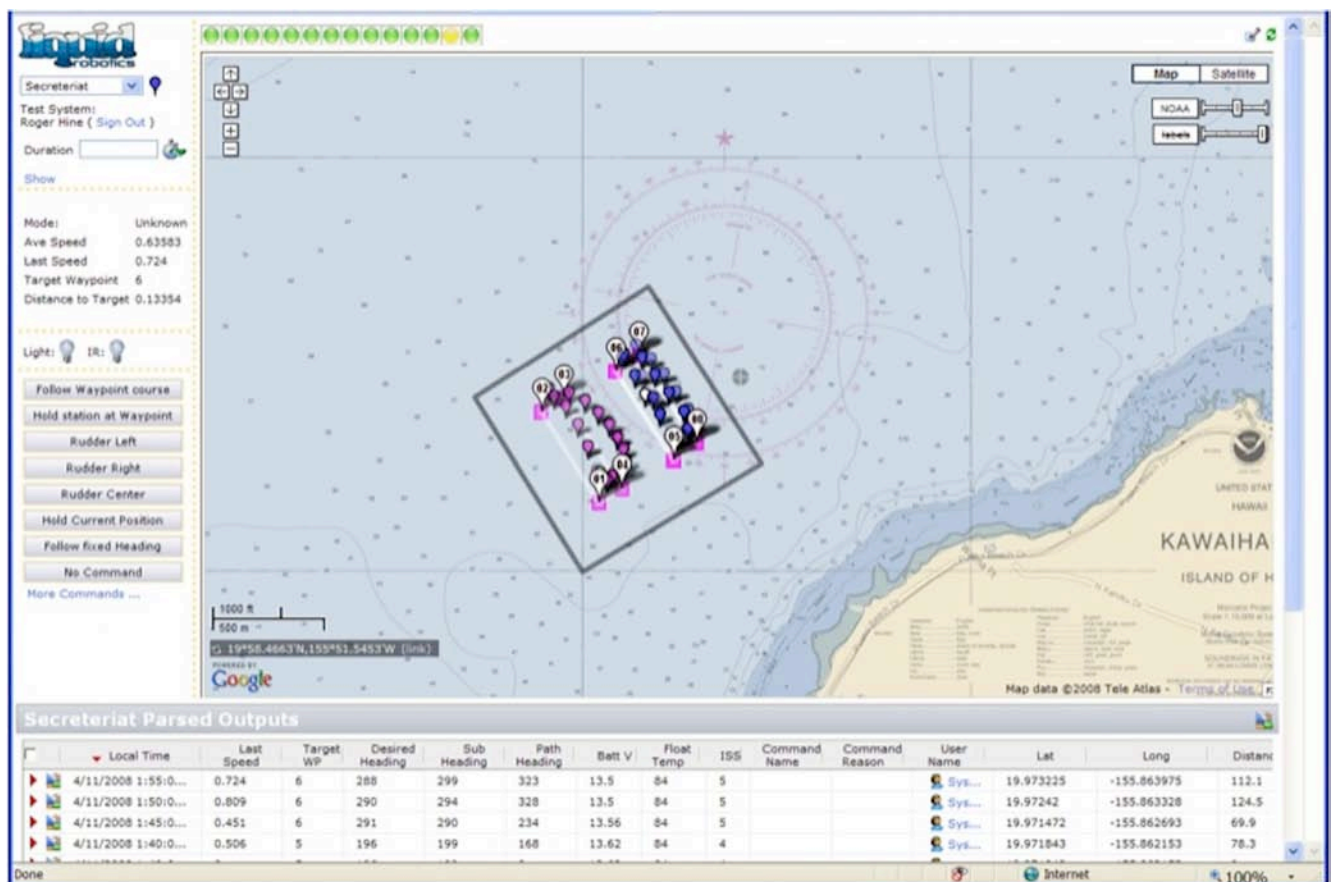


Figure 3: The Wave Glider User Interface

### Field results, Wave Glider performance at sea

Over the past two and half years, Liquid Robotics has undertaken a vigorous series of sea trials, driving prototype and product-level vehicle development programs. The current

production generation of the Wave Glider is the beneficiary of nearly six years of combined sea time and an estimated 60,000 cumulative nautical miles “sailed.” Liquid Robotics, with U.S. Coast Guard permission, maintains a test range offshore from Puako on the Big Island of Hawaii. Initial engineering trials and operational/acceptance testing of customer deliveries are conducted at the Puako test range. Once initial trials have been satisfactorily completed, additional testing to expose the Wave Glider to a wider range of sea conditions is conducted farther offshore.

The Wave Glider vehicle “Red Flash,” Figure 4, is an endurance leader in the Liquid Robotics fleet. This vehicle completed two significant demonstrations in 2009. First Red Flash circumnavigated the Big Island of Hawaii, January 9-18, 2009, a 343 nautical mile mission that the vehicle completed in 9 days, 2 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 second engineering trial and demonstration was conducted between August 13 and September 23, 2009 in which Red Flash, transited from Monterey Bay along the West coast of North America to Alaska. This mission lasted 41 days and covered just over 1300 nautical miles for an average speed over ground of 1.5 knots. During this mission severe weather exposed Red Flash to winds above 50 knots, swells exceeding 18 feet and peak wave heights of over 21 feet. Red Flash endured these conditions and maintained core functionality. The vehicle was recovered for inspection and the payload mast was found to have broken. As core vehicle antennas (GPS and Iridium) are directly deck mounted this did not endanger the Wave Glider itself. Improved masts, for payload sensors requiring elevation, are currently being designed based upon these recent results.



Figure 4: Red Flash, a well traveled Wave Glider

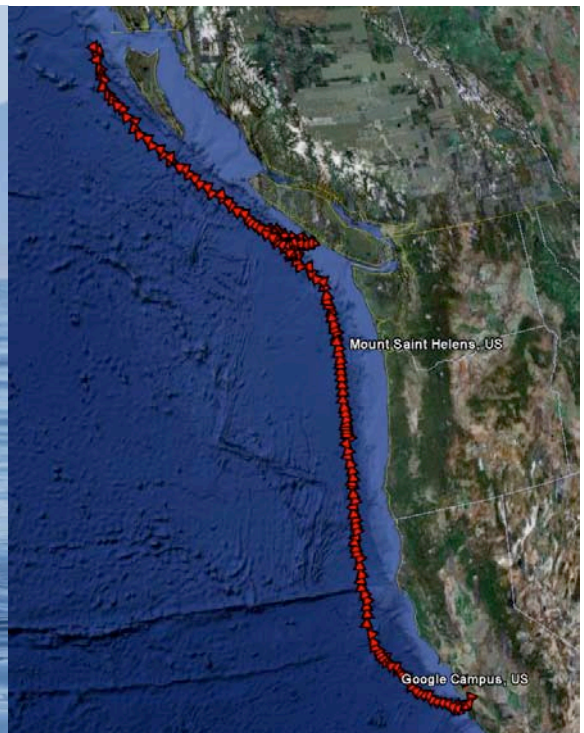


Figure 5: Red Flash's Voyage along the coast of North America

Additional long-term missions are currently underway, including multi-month, basin-scale ocean transits. Finally, as an engineering endurance trial, one Wave Glider has conducted a station-keeping mission in the Puako test range, augmented with frequent transits out into the open ocean. Initially begun as a 120 day demonstration for a customer, the test was significantly extended. After 154 days at sea the vehicle was briefly inspected by the customer onboard the Liquid Robotics support vessel. After 168 days it was briefly returned to shore so that the customer could remove their payload. The Wave Glider then returned to its station until December 15, 2009 when it completed 365 days of consecutive operation. At that time the vehicle was recovered to deck for a short, roughly two hour, cleaning and inspection. It then resumed its operation. Thus, at the time of writing, this

vehicle has completed over 418 days at sea with minimal maintenance, all while relying exclusively on natural energy for its operations.

## **A New Paradigm for Ocean Science**

As a persistent ocean platform the Wave Glider complements fixed buoys, undersea vehicles, drifters and vessels. The ocean is vast and observing requirements remain unmet by current platform availability. Regions beyond normal shipping lanes are especially difficult to access. Wave Glider's long-range capability and persistent station keeping make it well suited to observing in these areas. In sufficient numbers Wave Gliders can provide oceanographic data from transects across ocean basins. Additionally, areas of significance (e.g. upwelling sites, seamounts, marine protected areas) can be observed by station keeping Wave Gliders serving as virtual moorings. In operation near conventional oceanographic moorings Wave Gliders have demonstrated superior station keeping relative to the surface of the Earth. In one Monterey Bay experiment, Figure 6, a Wave Glider demonstrated a watch circle of better than 150 feet while a nearby mooring encompassed a circle over one mile in diameter. Mobile and stationary Wave Gliders, operating for up to one year without service, will greatly increase the number of platforms observing the ocean as well as their temporal and spatial distribution.

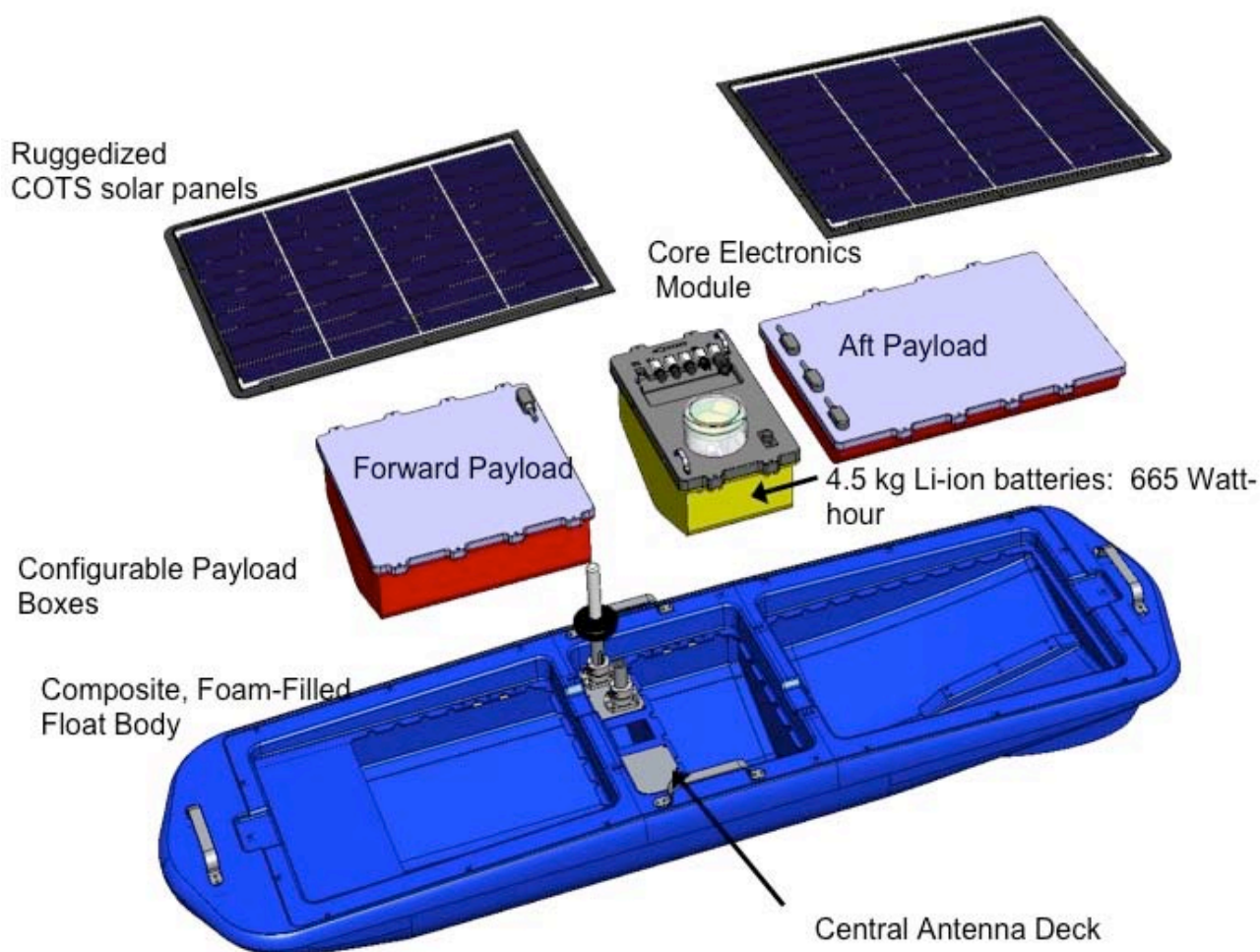


**Figure 6: Wave Gliders have demonstrated station keeping superior to conventional moorings**

Wave Gliders are affordable, with a similar capital cost as buoyancy driven UUVs (gliders). While their capital costs are modest, the potential savings in operations and maintenance are noteworthy. Wave Gliders do not require large vessel support. Liquid Robotics runs most operations from a 30 foot rigid hull inflatable. This is more than adequate to move vehicles beyond the immediate coastal region into waters deep enough for the vehicle's

operations. Deployments directly from shore have been demonstrated. Recovery is equally straightforward. During the Red Flash mission, described above, the vehicle was recovered by a commercial crab-boat. The captain and crew safely and effectively recovered the vehicle without formal training or any direct on-site support from Liquid Robotics staff. The use of vessels of opportunity to support Wave Glider operations is the anticipated norm. The smaller vessels required for these operations, and rarity of launch and recovery requirements, present a significant cost savings over conventional ocean platforms.

The Wave Glider is also quite versatile. The base vehicle has modular mechanical, electrical, and software interfaces to accept a wide variety of payload. Figure 7 illustrates the float modularity. All command and control, communications, and navigation electronics are contained in a core electronics module, which also houses the batteries and their charging electronics. Dedicated forward and aft payload compartments house most payload sensor systems and support electronics. These compartments can be fitted with watertight dry boxes or left open to splash and wash. There is ready access to surface waters for instrument probes. While the topside float provides a large volume and simple integration options the subsea glider can also support payloads. The tether between the float and glider carries power and communications. A subsea payload compartment is an available option and an industry standard connector is available for ease of integration.



**Figure 7: The Wave Glider is configurable to meet user's needs**

To date several payload systems have been demonstrated on the Wave Gliders, including passive hydrophones and towed hydrophone arrays, marine weather stations, still and video cameras, and acoustic Doppler current profilers (ADCPs). The current generation of the Wave Glider has also demonstrated towing 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, enabling new methods of data retrieval from undersea systems.

This payload flexibility has been applied to a variety of demonstration programs. Among other applications Wave Gliders have recently completed: 1) a demonstration of a seafloor to surface acoustic link for the National Oceanic and Atmospheric Administration (NOAA) tsunami warning network, 2) deployment of the Scripps Institution of Oceanography (SIO) high frequency acoustic recorder (HARP) for marine mammal monitoring and 3) deployment of a 600 kHz RDI Sentinel ADCP for surface current monitoring. Further discussions of recent and planned scientific programs are available in the cited references.

With significant experience derived from engineering trials and scientific demonstration programs Liquid Robotics is ready to apply the persistent ocean presence of the Wave Glider to ocean observation.

## References

Hine, R., S. Willcox, G. Hine, and T. Richardson. "The Wave Glider: A wave-powered autonomous marine vehicle." *Proceedings MTS/IEEE OCEANS 2009*, Biloxi, MS.

Manley, J., S. Wilcox, and R. Westwood. "The Wave Glider: An energy harvesting unmanned surface vehicle." *Marine Technology Reporter*, November/December 2009: 27-31.

Willcox, S., J. Manley, and S. Wiggins. "The Wave Glider, an energy harvesting autonomous surface vessel." *Sea Technology*, November 2009: 29-31.

Willcox, S., 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." *Proceedings MTS/IEEE OCEANS 2009*, Biloxi, MS.

## Acknowledgments

The Wave Glider has benefited from the support of customers and collaborators. The authors express their appreciation to their colleagues at Liquid Robotics and financial and in-kind sponsors of projects discussed here. These include, but are not limited to, The Jupiter Foundation, Teledyne RDI, SAIC, The National Oceanic and Atmospheric Administration and Scripps Institution of Oceanography.