The Wave Glider: A Persistent Platform for Ocean Science

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***Abstract* – The Wave Glider is an unmanned maritime vehicle (UMV) unique in its ability to harness ocean wave energy for platform propulsion. This paper provides an overview of the Wave Glider vehicle's design and capabilities, and presents results from the engineering sea trials 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. Scientific applications of the Wave Glider are presented through discussion of preliminary results and planned programs. Finally, we discuss several payload packages that have been or are currently being developed for the vehicle.**

I – INTRODUCTION: WAVE GLIDER TECHNOLOGY

The Wave Glider is a new class of wave-propelled, persistent ocean vehicle, Fig. 1. The key innovation of the Wave Glider is its ability to harvest the abundant energy in ocean waves to provide essentially limitless propulsion. The Wave Glider has previously been described [1, 2] but as it is a unique design a brief overview is appropriate.

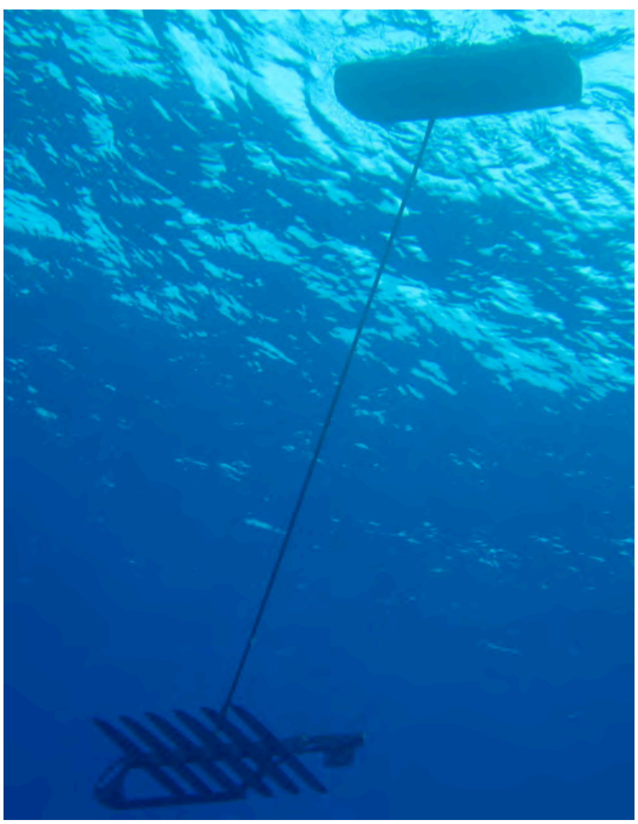

Figure 1: The Wave Glider from below

A. Architecture and Principle of Operation

Wave Glider is a hybrid sea-surface and underwater vehicle comprised of a submerged "glider" attached via a tether to a surface float. The Wave Glider 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.

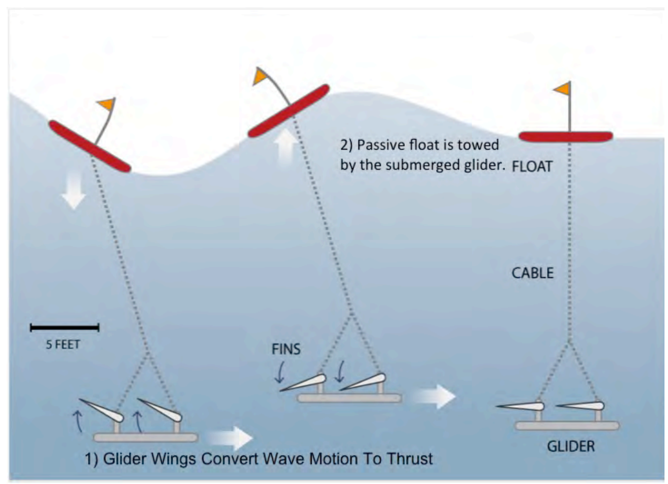

Figure 2: Wave Glider principles of operation

B. Platform Performance

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, 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.

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

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Glider demonstrated an ability to weather 10+ foot seas and 40+ kt winds. More recently, the Wave Glider "Red Flash" (Fig. 3) while surveying along the Alaska coast encountered 20+ foot seas and 50+ knot winds, Fig 4. In short, the Wave Glider has already demonstrated admirable robustness in strong seas over various deployments.

Figure 3: Red Flash off the Pacific Northwest

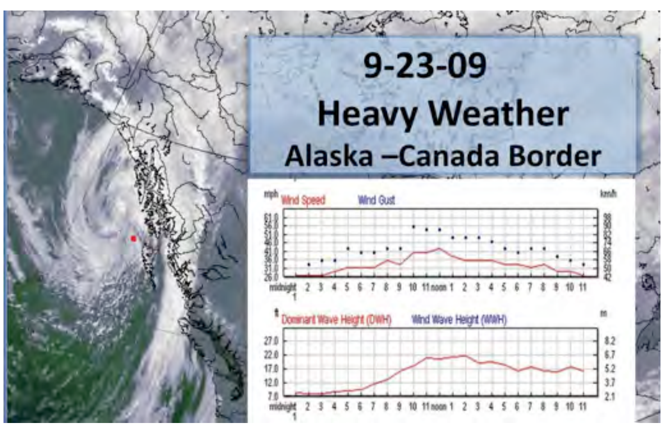

Figure 4: Conditions experienced by Red Flash (at red dot). Data courtesy Environment Canada

The opposite extreme of very calm seas represents a greater challenge to 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. 3 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). Note the obvious wake in Fig 3 despite the very limited wave state. Even in these extremely calm conditions, the Wave Glider is able to maintain a forward speed of 0.25 to 0.50 kts. Table I summarizes the anticipated performance of the vehicle in various conditions.

TABLE I

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

C. Sea Trials

Wave Gliders have completed many engineering sea trials including endurance tests and long voyages. Fig. 5 shows the tracks followed during several 2009 missions. The longest of these missions saw a pair of Wave Gliders navigate from Hawaii to San Diego. A single vehicle also transited from Monterey to Alaska.

Figure 5: Wave Glider extended voyages in 2009

Beyond covering long distances the Wave Glider has demonstrated exceptional robustness over time. The longest running individual Wave Glider began a customer sponsored 120 day endurance demonstration on December 15, 2008. At 82 days the vehicle tether was replaced after an incidental impact during an underway inspection. After a cumulative 164 days the customer requested the vehicle briefly return to dock so their payload could be removed. The vehicle immediately resumed operation and remained at sea off Hawaii until December 15, 2009 when it was briefly recovered to deck and some modest biofouling was removed. It was returned to the water and, as of March 8, 2010 the vehicle systems, including the replacement tether, had seen 365 days of operation at sea with the glider and float having endured more than 440 days of operation.

II – WAVE GLIDER APPLICATIONS

The Wave Glider was designed to accommodate a wide variety of payloads. It modular design, Fig. 6, offers ample volume for sensors. Solar panels and a battery system provide power for payload systems. Currently standard payload sensor systems are being planned so that users may order a Wave Glider with sensors and save significant time and complexity. As of early 2009 a variety of test and demonstration programs had been completed.

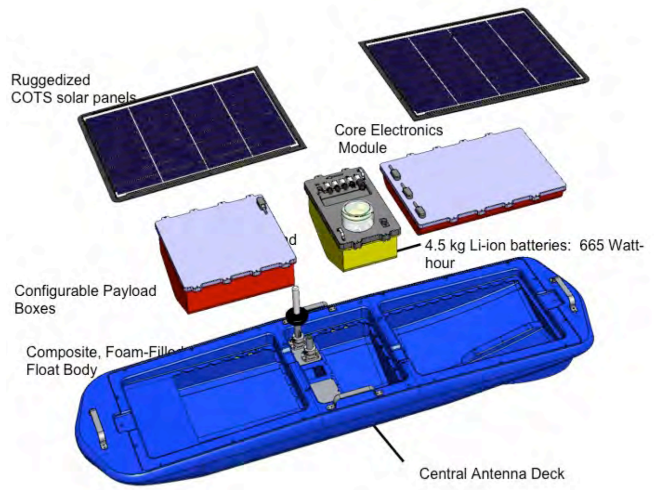

Figure 6: Wave Glider architecture is very flexible

Liquid Robotics collaborated with the Scripps Institution of Oceanography (SIO) to integrate the High-frequency Acoustic Recording Package (HARP) onto a Wave Glider. [3] The HARP was designed for long-term (up to one year) deployment as an autonomous bottom-mounted sensor for broad-band marine mammal monitoring. The HARP system consists of an acoustic sensor, signal preconditioning and sampling electronics, and a large data storage system. Several HARP systems are currently in use worldwide to acoustically monitor marine mammals for behavioral and ecological long-term studies.

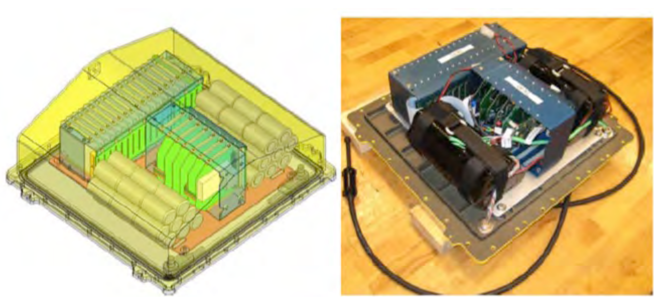

Figure 7: The HARP recorder in a Wave Glider payload box

Recently, SIO repackaged the HARP electronics into one of the Wave Glider's modular payload housings, Fig 7. The HARP hydrophone was towed behind the Wave Glider on a short cable. These preliminary tests indicated that the Wave Glider's nearly silent wave-powered propulsion make it an excellent host platform for the HARP and other acoustic sensor payloads. [4]

Another demonstration included the integration of a Teledyne RDI 600kHz Sentinel ADCP into a Wave Glider, Fig. 7. During this test program a series of trials were executed to evaluate the quality of the ADCP data. At the conclusion of these trials it was determined that the data, with the exception of that in the "bin" immediately around the glider/propulsor, was of good quality. New integration concepts, designed to eliminate the impact of the glider/propulsor in the data, are currently under consideration.

Figure 8: An ADCP integrated on the Wave Glider

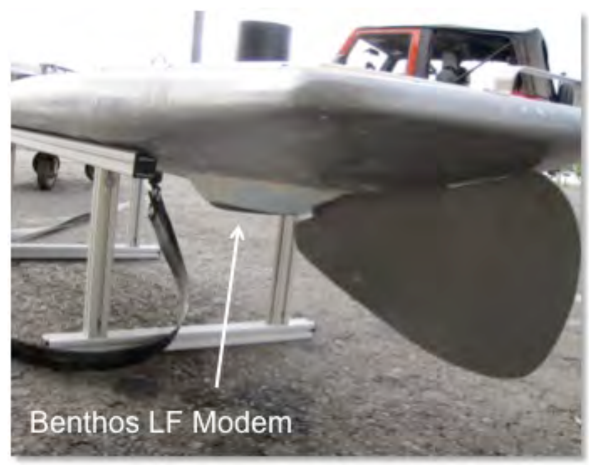

Figure 9: An acoustic modem installed in the float

Wave Gliders have also carried acoustic modems to provide connectivity between subsea systems and shore. Field programs have used Benthos low frequency acoustic modems to demonstrate this capability. Initially the modem transducer was mounted to the undersea glider/propulsor. While this provided good acoustic performance the configuration proved sub-optimal for Wave Glider operations. Thus the transducer has subsequently been integrated into the float, Fig. 9. Acoustic trials of this configuration are planned for April 2009.

To evaluate the Wave Glider's capabilities as a "virtual mooring" an April 2009 experiment saw the Wave Glider operate in the vicinity of M2, a conventional science buoy operated by the Monterey Bay Aquarium Research Institute (MBARI). When operated in close proximity, Fig 10, the Wave Glider was able to compare both its station keeping performance and sensor data to that of M2. In both cases the results were positive. The sensor data closely tracked that on the mooring, with the exception of air temperature where a constant offset was observed. It was hypothesized that the height difference between the Wave Glider sensor and that on M2, readily visible in Fig. 10, was the source of this error. The station keeping performance of the Wave Glider was significantly better than M2. While the mooring saw a watch circle of 1700 meters (a consequence of the scope on its anchor chain) the Wave Glider held station within a 50 meter radius.

Figure 10: Wave Gliders compare well to moorings

Finally, the NOAA Pacific Marine Environmental Laboratory and Liquid Robotics, Inc., are collaborating to address an urgent need for long-term *in-situ* observation of carbon parameters over broad swaths of the global coastal and open ocean. By integrating a suite of state-of-the-art pCO_2, pH, and CTD sensors onto a Wave Glider The resulting Biogeochemical Wave Glider, Fig. 11, will be capable both of acting as a long-duration (up to 1 year) "virtual mooring" to augment the existing sparse collection of moored carbon science sensors. It will also be capable of conducting autonomous, basin-scale ocean transits to provide new insight into the spatial variability of carbon uptake and associated parameters. Key to this capability will be the incorporation of the MAPCO2 sensor currently deployed by PMEL in traditional moorings. This instrument is able to provide carefully calibrated data over long-time scales, making it an excellent complement to the Wave Glider. [5]

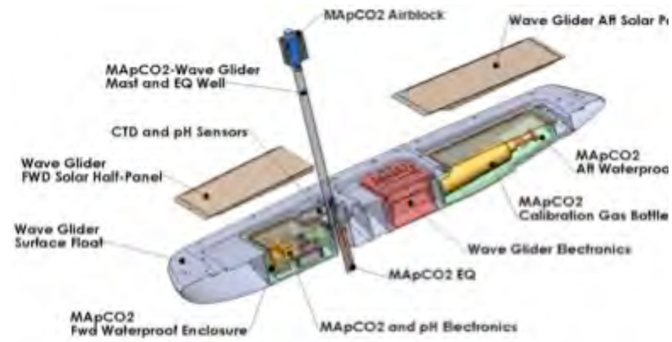

Figure 11: The anticipated biogeochemical Wave Glider

III – CONCLUSION: NEW OPPORTUNITIES

Since the inception of Liquid Robotics in 2007 the Wave Glider has matured rapidly. Rigorous sea trials in diverse conditions have validated the functionality of the core platform. The ocean science community can now consider entirely new science programs covering large temporal and spatial scales. The low capital and operating costs of Wave Glider enable experiments based upon "fleets" of these vehicles.

As a persistent ocean platform the Wave Glider complements fixed buoys, undersea vehicles, drifters and vessels. The ocean is vast and observing requirements are not met by current platform availability. Regions beyond normal shipping routes are especially difficult to access. Wave Glider's long-range capability and persistent station keeping make it well suited to observing in these regions. 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. 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.

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 Wave Gliders. Deployments directly from shore have been demonstrated. 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.

Demonstration programs to date have confirmed the suitability of Wave Gliders for many oceanographic sensors. Over the course of 2010 new payloads will be integrated into the Wave Glider and more demonstrations will be completed.

Peer-reviewed articles based upon new data otherwise unavailable, or unaffordable, are not far behind.

ACKNOWLEDGEMENTS

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