Ten Years of Wave Glider Operations: A Persistent Effort

Justin E. Manley
Just Innovation, Inc.
Boston, MA USA
jmanley@alum.mit.edu

Ryan Carlon, Graham Hine
Liquid Robotics Inc.
Sunnyvale, CA

Abstract - The Wave Glider® is a unique wave and solar energy powered Unmanned Surface Vehicle (USV). Development of this technology began in 2005 and in 2007 the company Liquid Robotics was created to bring this product to market. In the ten years since the company was founded the Wave Glider and the entire field of USVs has evolved significantly.

Lessons learned revolve around three primary themes: technology, marine operations and human factors. All of these areas saw distinctive experiences and outcomes driven by the outlook of Liquid Robotics as a Silicon Valley startup company. The approaches and assumptions of such an entity are often different from traditional ocean technology developers.

In technology a product development approach can yield accelerated results but certain ocean engineering challenges take time to address. In marine operations considerations of the environment and launch and recovery are addressed through experimentation and adaptation. In human factors leverage of unmanned systems and attention to regulations are key lessons learned.

I. WAVE GLIDER INTRODUCTION

The Liquid Robotics Wave Glider is an unmanned surface vehicle (USV) consisting of a surface float connected to an underwater sub with wings via a flexible umbilical. Just as an airplane's forward motion through the air allows its wings to create an upward lifting force, the vertical motion of the sub through the comparatively still and deep water allows its wings to convert a portion of this upward motion into forward propulsion. Lithium ion batteries recharged via solar panels provide power for system electronics, communications and sensor payloads. The system communicates in near real-time via two-way Iridium satellite radio. The Wave Glider operating environment allows multiple navigation modes from pre-programmed complex courses to active piloting from shore as well as features such as AIS-based ship avoidance. As an extensible platform, there are many locations for sensors to be attached, with standard interfaces for power, communications, and back seat autonomy. Payloads can be mounted on the masts, in various locations in or on the float, attached to the underwater sub, or towed behind the underwater sub. The Wave Glider can be deployed for periods of many months and travel great distances. The concepts and capabilities of the Wave Glider are discussed at length in [1] [2] and [3].

The latest generation of the Wave Glider includes many features that improve upon the initial offering. These include increased solar panel and battery capacity and a rudder mounted thruster known as a thrudder (Fig 1). Together these improvements offer the Wave Glider an expanded operating envelope. This current capability is a result of over ten years of technology development. Over these ten years and hundreds of deployments, significant lessons have been learned. The perspective of a Silicon Valley "startup" rather than more traditional defense or scientific research programs inspired much of this history.

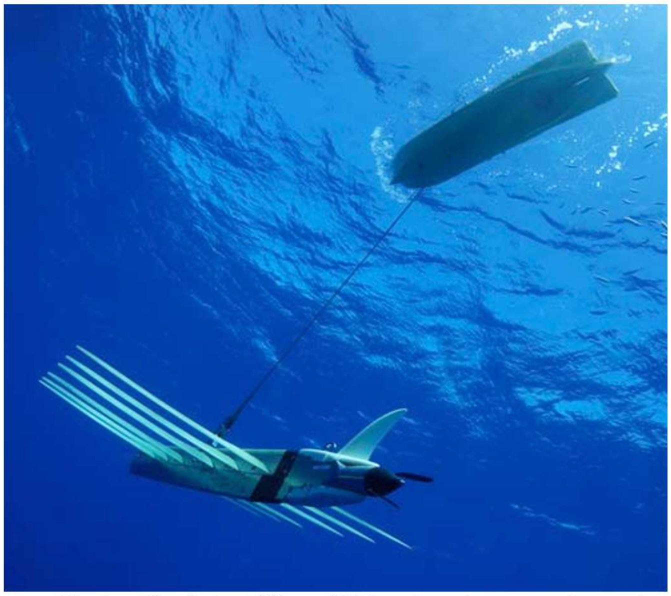

Fig 1 – The latest Wave Glider showing new elements such as the "thrudder"

II. TECHNOLOGY LESSONS

The development of the Wave Glider was driven through a commercial product development approach. This is in contrast to many unmanned maritime vehicles (UMVs) that were developed under defense research programs. During 10 years of development multiple generations of the Wave Glider USV were evaluated, thoroughly tested and advanced to production. This is a faster pace of technology development than has been seen in other UMV efforts. A product management approach inspired by Silicon Valley yielded significant lessons, while the traditional challenges of ocean technology were also addressed

A. Product Management

Product management is driven by customer insights and a vision for how the future can be different with change. Successful products address not just the challenges of today, but ones that may arise in the future. The product management team must take into consideration the full range of attributes that inform customer needs and buying behavior – flexibility, durability, size, price and more. They must translate these needs – across multiple buyer types – into a vision and set of requirements for engineering teams.

The rubber meets the road, or perhaps the hull meets waves, as engineering teams build and test the capabilities needed to bring a product and vision to life. As capabilities are developed, product management must balance the time and resources required to create and test them with the need to get meaningful product into the marketplace. Of course, not all requirements can be met. Or meeting stated requirements may cost too much money or take too much time. Again, the product management team must work with engineers to strike a balance that allows them to deliver differentiated products into the market.

Several examples of this approach applied to the Wave Glider have been seen over the past ten years. They include:

Configuration: While many UMVs developers attempted to offer custom solutions for each user the Liquid Robotics strategy was to focus on producing a platform and a few key configurations, rather than taking on responsibility for all configurations. The decision was made to avoid attempting expertise in dozens of highly specialized applications and rather enable customers to take the platform and customize it, thus serving those applications successfully.

Testing: Even before Liquid Robotics was founded the value of field-testing was noted. Thus an operations facility in Hawaii was established to allow continuous access to the ocean. With reliability such an important factor to any ocean technology product's commercial viability, it's critical to get time at sea in real-world conditions with real product, and that requires continuous investment in testing.

Iterating: Rapidly learning from customer experience and iterating products is a key product management concept. The Wave Glider platform demonstrated this through a very fast cycle from prototype to product. A key example of this cycle was the recognition that to address significant ocean currents an auxiliary thruster would be beneficial. This feature appeared on the second generation Wave Glider delivered to market only five years after the first (Fig 2). A similar evolution in undersea vehicles driven by classic research program drivers took over ten years to come to market.

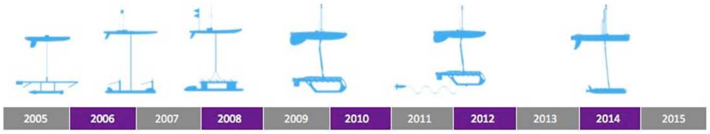

Fig 2 – The Rapid Product Development Cycle

B. Engineering for the Ocean

While the product development approach can accelerate time to market there were many ocean engineering challenges to address that slowed the process. The harsh physical environment of the ocean and the wave propulsion design of the USV were especially complex. This demanded continual design and manufacturing assessment and development. For example, the components, fastening and design of the core umbilical between the float and sub have continued to evolve as higher sea states have encountered. Eventually this component design was optimized so that users could adapt the system to their most likely operating environment while relying on the system to function through hundreds of thousands of propulsion cycles.

Corrosion and biofouling are also important concerns in the ocean environment. Any system designed for extended ocean deployment must address both. In the case of corrosion careful materials selection was critical. But especially with components exposed to electrical current, like connectors, only significant field experience can determine the optimal subcomponent and material choices. Over time the design evolved to minimize penetrations, thus reducing connectors and seals. Both of which were vulnerable to environmentally induced failures.

Fig 3 – Biofouling on the sides and bottom of the float

Fig 4 - Biofouling on the sub and wings

While corrosion can be addressed through engineering choices, biofouling is much harder to address by design. It was necessary to take time to understand the impacts of this natural phenomena. With extended deployments the impacts of biofouling on the float (Fig 3) and sub (Fig 4) could be observed. In the course of this observation it was determined that even at maximum fouling coverage the sub function was unimpaired and the overall drag impacts on the float were minimal. Thus while biofouling occurs, it was not a significant negative impact on the platform.

Time and attention to the unique aspects of ocean engineering complement the more rapid approach of product development.

III. Marine Operations Lessons Learned

As an energy independent system, the Wave Glider enables many new approaches to maritime operations. From ocean crossings to vessel independent research programs the Wave Glider has driven innovation in marine operations. This experience has been shaped through customer engagement and experience from an array of diverse missions and ocean conditions.

A. Environment

With any marine technology it is important to understand the environment and the limitations it imposes. Early concerns included risks posed by extreme weather such as hurricanes. However over time this concern was mitigated through experience. To date Wave Gliders have been exposed to 17 hurricanes. While some damage in these cases is inevitable the overall experience shows extreme waves and wind to be manageable. One example of this was the Wave Glider Benjamin, which was part of a cross-pacific voyage known as PacX. As part of this voyage the system encountered Tropical Cyclone Freda, on 31 Dec 2012, northwest of New Caledonia. Rather than a risk of failure the encounter become a scientific opportunity. [4]

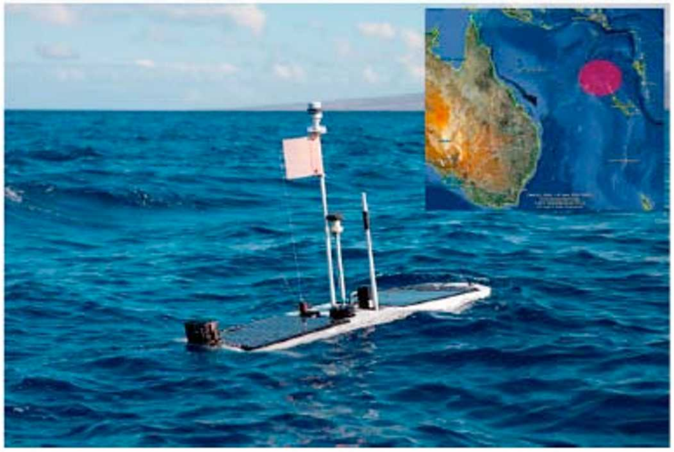

Fig 5: Wave Glider *Benjamin* and the area where it glider encountered Tropical Cyclone Freda.

Of greater concern to wave glider operations were regions of low wave energy and high currents. Currents above one knot challenged early versions of the wave glider, especially when wave energy was modest. In such conditions vehicles had trouble making headway and holding station. Some saw their float/sub orientation impacted by twists in the umbilical. [5] While experienced operators learned to plan and adapt to these conditions, the engineering team saw an opportunity to address this challenge and developed an electric "thrudder" to provide auxiliary thrust to address these types of operating conditions and challenges.

B. Launch and Recovery

All maritime technologies must reach the ocean. The Wave Glider was designed to stay at sea for long periods of time. To deliver on the value proposition of a persistent platform it is important to minimize the demand for ships and personnel for the unavoidable launch and recovery cycle. After all, if you're always watching over your unmanned system with people, it's not really unmanned. To address this challenge with Wave Gliders it was necessary: a) make launch and recovery infrequent by leveraging the ability to run long-duration missions with high reliability and b) make both launch and recovery easy with subsystems, tools, training, and a focus on small craft support.

The duration and durability of Wave Gliders has been widely discussed elsewhere. Launch and recovery is hard to generalize as it is typically optimized for specific platforms. However they general process developed for the wave glider focuses on a quick deployment of a "zipped up" wave glider on a davit. Upon immersion the sub is released initiating the propulsion rapidly away from the host vessel. This process was perfected through significant field experience and is compatible with most weather conditions. Recovery can be more challenging but is made simpler by the persistence of the platform. Rather than focus on complex recovery tools operators can plan recoveries around longer operating windows and simply wait until conditions are right for the more complex operation. In short, if weather or other issues change a desired recovery window, the Wave Glider, given it's wave powered propulsion, can wait in one area or swim to another to meet changed needs.

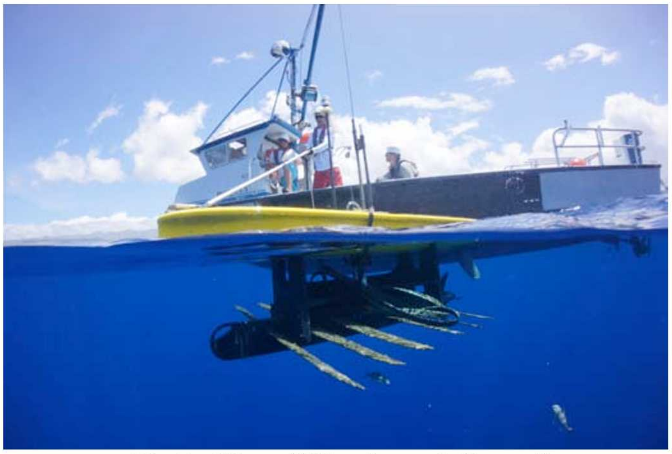

Fig 5 – Wave Glider Launch Operations

C. Experiment and Adapt

The ocean is complex. Wave Gliders are affected by wind, temperature, currents, salinity, waves, bathymetry, traffic, sun, clouds, and precipitation. Modeling how a system responds to all of them is only possible at a basic level. Ultimately you have to put vehicles in the ocean, the true operating environment (as opposed to a tank). Therefore a key lesson learned is to make operations easy on engineers and developers. With a Hawaii facility, engineers can put a prototype in the water in the morning, evaluate its performance against a baseline system, pick it up, adjust it, and redeploy it, sometimes completing that whole cycle twice in one day. That means one can rapidly close on an optimal solution.

It is also important to learn from customer missions. When a customer finds the edge of the envelope, engineers work with them to learn what happened and expand that envelope. It was through this process of rapid evolution and customer engagement that the use of the Wave Glider as a towing platform evolved. [6] With this new capability a series of new applications were unleashed. These included monitoring of marine mammals, seafloor seismology, and fisheries surveys. [7, 8, 9, 10]

IV. HUMAN FACTORS

While "unmanned" systems may not have pilots or sailors on board they still demand attention from human beings. At sea, especially for launch and recovery, and ashore supporting global operations, the role of people in USVs is critical. Over the past decade best practices with such factors, as well as with policy issues such as collision avoidance, have evolved. There are important lessons learned in the "people problems" with unmanned systems.

A. Leveraged Operations

In the early days of Wave Glider operations multiple technicians and operators might be required to deploy, oversee and support a single Wave Glider. As the basic platform engineering was resolved it became not only possible, but practical, for the same logistics footprint (people and vessels) to support multiple Wave Gliders. On deck the reliability of the system ensured a deployment did not need to save time or space for pre-launch debugging. Scenes such as Fig 6, five systems deployed by one small vessel, became common. The increased value to owners and operators in this case is quite clear. This kind of deployment significantly leverages existing infrastructure.

Fig 6 - Deploying multiple Wave Gliders on a single vessel

Once at sea Wave Gliders are largely independent of human supervision. Sophisticated on board diagnostics ensure issues are brought to the attention of operators in a timely manner. Equally capable control interfaces, such as Fig 7, allow a small number of operators to oversee significant fleets. Customers have successfully executed missions with dozens of units collaborating through software based oversight and control. As autonomy and AI becomes ever more capable this trend will continue.

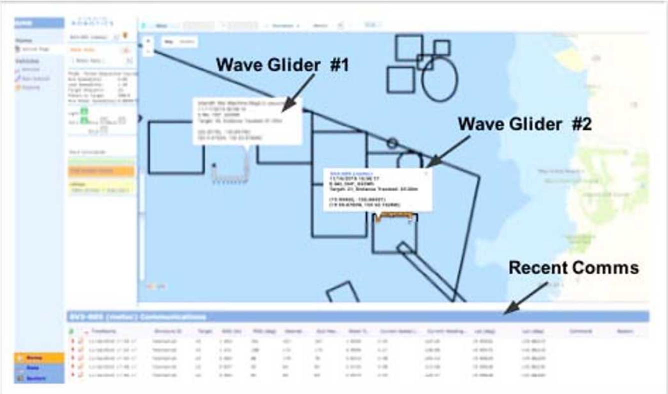

Fig 7 – Multi-vehicle monitoring and management in one interface (the Wave Glider Management System)

B. Regulation

While technology moves fast policy and regulation can often lag behind. In the first few years of Wave Glider development the very idea of an unmanned vessel was unique. This facilitated a healthy dialog with regulators such as the US Coast Guard. Seeing that the operations in question were rare it was easy to reach an accord and allow the engineering trials. In those days given the small form factor and rarity of appearance the systems were considered "marine debris" and simple notices to mariners served to address rules and regulations.

Since then more rigor has come to operations of Wave Gliders, and all USVs. Global operators have worked with numerous navies, coast guards and marine sanctuaries to develop robust policy. The big picture for all UMVs is evolving and largely favorable. [11] Ideally we will see all UMV operations viewed as those seen by Wave Gliders in Hawaii, where the local community has come to appreciate their presence as a positive contribution to the overall ocean ecosystem. But as with all regulations and policy constant attention to both law and best practices is critical to ongoing success.

V. CONCLUSIONS

The Wave Glider concept has come a long way since 2007. In fact in 2015 cumulative Wave Glider operations surpassed 1,000,000 miles. This is a result of some new approaches, especially a product management outlook, but has addressed many long-standing challenges to ocean technology that required time and testing to overcome. Field experience drives the evolution of both technology and applications. New approaches to ocean operations are enabled by persistent USVs. Leveraged operations allow greater return on investment in limited assets such as vessels and staff. New approaches to important scientific missions have been enabled by the rapid development of USV technology and products like the Wave Glider.

While technology has evolved significantly in the past ten years, unmanned systems are still intimately tied to human beings. Launch and recovery and regulatory concerns require careful consideration of people and policy. It will be critical for developers, operators and regulators of all UMVs to continue an open dialog. Fair-minded development of rules and broad distribution of best practices should ensure another ten years of exciting, and beneficial, developments.

Acknowledgements

The authors are indebted to their many colleagues at Liquid Robotics, and many customers and partners, who have been part of the development of these lessons learned. All images are courtesy of Liquid Robotics.

References

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

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

[3] Manley, J. and S. Willcox. "The Wave Glider: A Persistent Platform for Ocean Science," *Proceedings of IEEE OCEANS 2010,* Sydney Australia, May 2010.

[4] Lenain, L. and W. Melville, "Autonomous Surface Vehicle Measurements of the Ocean's Response to Tropical Cyclone Freda," American Meteorological Society Journal of Atmospheric and Oceanic Technology, October, 2014

[5] Manley, J. Leonardi, A., and C. Beaverson, "Research to Operations: Evaluating Unmanned Surface Vehicles," *Proceedings of MTS/IEEE OCEANS 2016*, Monterey, California, September 2016.

[6] Manley, J., and G. Hine, "USVs as Tow Platforms: Wave Glider Experience and Results," *Proceedings of MTS/IEEE OCEANS 2016*, Monterey, California, September 2016.

[7] Wiggins, S., J. Manley E. Brager and B. Woolhiser, "Monitoring Marine Mammal Acoustics Using Wave Glider," *Proceedings of MTS/IEEE OCEANS 2010*, Seattle, WA, September 2010

[8] Laske, G., Berger, J., Orcutt, J. and Babcock, J., ADDOSS: Autonomously Deployed Deep-ocean SEismic System - Communications Gateway for Ocean Observatories, Geophysical Research Abstracts, 16, Abstract EGU2014-4707, 2014

[9] Meyer-Gutbrod, E., C. Greene, and L. McGarry, "Wave Glider Technology for Fisheries Research, New Integrated Instrumentation Expands the Fisheries Acoustics Toolbox," *Sea Technology*, December 2015.

[10] Greene, C.H., E.L. Meyer-Gutbrod, L.P. McGarry, L.C. Hufnagle Jr., D. Chu, S. McClatchie, A. Packer, J.-B. Jung, T. Acker, H. Dorn, and C. Pelkie. 2014. A wave glider approach to fisheries acoustics: Transforming how we monitor the nation's commercial fisheries in the 21st century. Oceanography 27(4):168–174.

[11] Lebouvier, R. et. al. "Unmanned Maritime Systems and the International Regulations for Prevention of Collisions at Sea (COLREGS)" *Proceedings of XPONENTIAL,* AUVSI New Orleans, May 2016.