FROM BIG WAVES TO COLD WATER – UNIQUE MISSION REQUIREMENTS AND RESULTS FROM UNMANNED SURFACE VEHICLES

Kellie Keller* **and Rajesh Jha†**

Taking ocean measurements in 6M waves and remote locations is often best suited to unmanned vehicles. With 10 years of operations, Liquid Robotics and its partners continue to discover the value of collaboration with both customers and scientific organizations. In this whitepaper, we will discuss the range of platform and sensor requirements for the Liquid Robotics Wave Glider, an unmanned surface vehicle(USV), with a focus on challenges and successes from missions in the Arctic and a mission in the North Sea as part of the MASSMO3 experiment series that supported the Royal Navy's 2016 Unmanned Warrior exercise in Scotland.

INTRODUCTION

In a March 1961 message to Congress, President John F. Kennedy, Jr. wrote, "Knowledge of the oceans is more than a matter of curiosity. Our very survival may hinge upon it." Fifty-six years and a technology revolution later, the same thought prevails. We have successfully landed on the moon and produced a space-based telescope to view the reaches of the universe, yet our exploration of the ocean has progressed at a fraction of our space investigation. With an exponential increase in the global population occurring over this same period, the planet upon which we live has become a very different place in a short span of time. Given the critical role that the ocean plays in our ecosystem, the need for greater study and understanding cannot be understated. Fortunately, the technology revolution and the results of Moore's law have yielded advances in autonomous systems, artificial intelligence, and big data providing us with a new set of powerful tools and the capability to tackle challenges such as the gap in our understanding of the ocean in new and faster ways.

Studying the ocean is not limited to one country or one technology, and the insights gained impact the entire globe. Collaboration and cross communication are essential elements in both developing the systems to study the ocean and sharing the results of these studies. The unmanned systems market continues to grow and evolve, putting robots into roles typically labeled as dully, dirty and dangerous. As risk mitigation tools, unmanned systems reduce the logistical burden and safety concerns in some of the most unforgiving environments.

For the past two decades, a large emphasis was placed on the unmanned vehicle—ground, aerial, surface, and subsurface—versus the payload it could carry. After the 9/11 terrorist attack in the United States, a preponderance of unmanned systems, specifically unmanned aerial systems

* Kellie Keller, Sr. Director Program Management, Liquid Robotics, 1329 Moffett Park Drive, Sunnyvale, CA 94089.
† Rajesh Jha, Manager Software Engineering, Liquid Robotics, 1329 Moffett Park Drive, Sunnyvale, CA 94089.

flooded the market and became an instant combat force multiplier, initially in Afghanistan and Iraq. Plagued by a lengthy acquisition process, DoD began a contracting practice in 2009 coined "rent a drone" to satisfy the ground combat commanders' needs for imagery.* This distinct focus on the information collected versus the platform design signaled a major shift in both US defense acquisition approach and in commercial industry offerings. This shift towards the use of "off-the-shelf" technologies that could be quickly customized also drove a need to look at the interfaces between the payloads (or sensors) and the vehicle.

Leveraging the knowledge gained from UAVs and other fixed mounted sensors across myriad industries, the Liquid Robotics Wave Glider provides an elegant, cost effective solution to host sensors and to operate in most ocean environments. Since the founding of Liquid Robotics in 2007, Wave Gliders have operated in every ocean and accumulated over 1.2M nautical miles at sea. Operating at the surface with a sub-surface expression that extends from 8-20M below the surface, the Wave Glider provides an essential gateway between the seafloor and space. Integrated navigational positioning enables the Wave Glider to hold station like a buoy or autonomously navigate to mission locations, collecting data and sending it in real time to decision makers. Measuring persistence in months and up to a year, the Wave Glider plays a fundamental role in extending networks and data collection in the maritime environment.

THE LAST TEN YEARS

While many problems can be anticipated, nothing beats practical experience to illuminate ways to improve the performance of equipment in harsh environments. Wave Gliders have had years of exposure to the worst the ocean can offer, and design changes impacting everything from communications to propulsion have resulted from this exposure. One can imagine how a platform will respond to being run into an iceberg, but seeing it impact, turn aside and swim away unharmed provides key validation of a robust design. With high data transmission costs, there is an opportunity to intelligently synchronize data collection from the various sensors and carefully determine which data to transmit now, and what to store for post-mission analysis. Onboard processing and fusion of data from multiple sensors can also be used to make real-time mission decisions. Looking to the future, artificial intelligence and machine learning advances will rapidly help the scientific community respond to data in real-time.

COLLABORATION WITH RESEARCHERS

Working side by side with world renowned scientific researchers from organizations such as the National Oceanic and Atmospheric Administration (NOAA), Monterey Bay Aquarium Research Institute (MBARI), Scripps Institution for Oceanography, Jupiter Research Foundation, Liquid Robotics has established an ecosystem of research institutions and partners who leverage the value of unmanned systems to achieve goals that would not be possible or affordable using traditional approaches.

The impact of this collaboration cannot be understated and continuously motivates the teams that design our platforms and integrate sensors. Each mission heightens the awareness of the teams – from mission operations to engineering - about the potential of unmanned systems in ocean research and the total system performance of Wave Gliders equipped with different payloads and sensors. And while each mission possesses its own unique challenges, missions in extreme latitudes such as the Arctic and Southern Oceans or in areas with harsh conditions – like the North Sea -

* Whittle, Richard. DoD Tries Buying Pixels, Not Planes, For Flexible ISR; It Ain't Leasing. Website. Breaking Defense. http://breakingdefense.com/2012/05/dod-tries-buying-pixels-not-planes-for-quick-flexible-isr-it. May 7,2012. Accessed March 4, 2017.

have provided invaluable insights to operating unmanned systems in harsh and difficult environments.

WAVE GLIDERS IN THE ARCTIC

Liquid Robotics and its customers have run missions in the Arctic from 2011 through 2015. Some quick statistics include the following:

- 5 missions – 2 science, 3 commercial / industry
- 18 different vehicles on missions
- 2 generations of Wave Glider vehicles (SV2 and SV3)
- 8 different configurations of sensors and vehicles
- 900 days at sea
- 36,000 nautical miles surveyed

Wave Glider missions in the Arctic from 2011 to 2015

In 2014, Liquid Robotics had incorporated feedback from a range of missions around the world to introduce a new platform, the Wave Glider SV3. This platform offered greater propulsion (an electric thruster), expanded power management, new navigational capabilities, and the ability to support an expanded set of sensors. With new capabilities, customers sought to both gather new data and evaluate performance of the platform to support future science and commercial operations in the Arctic.

The Value of Planning and Software at 70 Degrees North Latitude

Liquid Robotics performed two missions in the upper Arctic latitudes between 2014 and 2015. The missions, which included an ADCP, demonstrated the value of a software driven platform and sensor integration with real-time communications. In the 2014 mission, despite planning and known assumptions about the magnetic environment, the degradation in compass performance varied unpredictably and had a corresponding variable impact on the software algorithms used for navigation. An engineering team in Sunnyvale, CA saw the problem occur in real-time and responded. They developed, tested and implemented a new navigation algorithm on the Wave Glider in the Arctic within hours allowing the mission to proceed. The Wave Glider now had greater operational and navigation parameters allowing it to better operate in various directions and currents. A catastrophic loss was avoided because of reasonable assumptions made by the software engineering team and the inclusion of redundant navigational systems.

On the same 2014 mission, the team looked to understand currents utilizing a Teledyne 300kHz ADCP and a GPS-based Wave Height Sensor based upon a LORD MicroStrain GX3-35 (GPS+IMU). During the mission with real-time analysis of the data, the team determined that the ADCP's internal magnetic compass was not reliable at higher latitudes for useful currents heading information. The magnetic challenges that affected the vehicle were also presenting challenges for sensors that used vehicle heading and positional data.

To resolve the problem, the team used data from the MicroStrain GPS to correct the ADCP data. This required synchronizing the ADCP and MicroStrain data collection to maximize the usable ADCP data for re-processing. While this may appear like a simple time reconstruction challenge, it depended on the sample rate of each sensor. The sensor sampling rates were set by end-users based on the operating environment parameters (power availability, time of day, etc.). The ADCP collected data for 12 minutes every hour and the MicroStrain collection occurred once every 90 minutes. To resolve the problem, the team needed to extend the duration of ADCP sampling. The Wave Glider allowed this change to occur in real-time and allowed other vehicle parameters to be adjusted to offset greater power consumption from the ADCP sensor. With longer duration ADCP sampling the team created a usable data set for study and analysis.

After successfully completing the 2014 customer missions, the team had gathered a wealth of information on how to improve platform and sensor performance in high latitudes, cold water, and reduced solar generation environments. This resulted in improved mission planning to address sensor synchronization and power management for future missions.

2015 Arctic Missions

A follow on 2015 mission leveraged the 2014 lessons learned to improve data collection. The sensor configuration included:

- Three SV3 Wave Gliders with METOC sensors (Weather Station, Wave Height, and an ADCP)
- A 300KHz ADCP configured to collect raw single ping currents at 1HZ in beam coordinates, using 30 bins of size 4m each with bin 1 starting at approximately 6m
- ADCP data output as RDI's PD0 format and collected in the payload Sensor Management Computer filesystem
- ADCP's internal compass based heading being recorded in the individual single ping data ensemble, but not used for any processing
- NAV data block appended to each ensemble with system GPS & time, latitude, longitude as per RDI's NAV data block format
- MicroStrain (GX3-35) configured to output GPS and AHRS (IMU) at 4HZ each with raw data collected in the Wave Glider payload Sensor Management Computer filesystem

The objective of the setup was to correct the synchronization deficiencies, evaluate compass performance, and generate a usable research data for further study. This data set included ADCP and MicroStrain data collected on each vehicle during the period 02-July-2015 (start of mission) and 31-August-2015 (end of mission), collecting when each vehicle was powered on for varying days and weeks, depending on location and power status.

For each weekly data set from each vehicle, the team generated data and reports that included:

- Plots of processed currents east and north components, currents direction, currents magnitude, vehicle heading (using GPS data), using the MicroStrain IMU yaw heading and MicroStrain GPS
- Plots of processed currents east and north components, currents direction, currents magnitude, vehicle heading (using GPS data), using ADCP compass heading and ADCP NAV data GPS
- Plots of ADCP heading and GPS based currents magnitude at selected bins over a 2-hour duration, MS heading and GPS based currents magnitude at the same selected bins and duration, vehicle speed magnitude during that duration
- Plots of ADCP compass heading, MS yaw heading for a two-hour duration

The results reinforced the unreliability and unpredictability of the ADCP magnetic compass at higher latitudes. The MicroStrain GPS+IMU helped to normalize the ADCP measurements, despite some noise in the MicroStrain IMU magnetometer, resulting in a successful mission.

There are a range of challenges when operating in the Arctic with both manned and unmanned systems, especially at latitudes above 70 degrees. Key lessons learned included:

- Magnetic compasses are unreliable and can cause unexpected problems for navigation algorithms and sensors. Unmanned systems need the flexibility to adapt both navigation and sensors activity in real-time as well as redundancy.
- Plan for logistics challenges with deployment by building in a buffer to operational assumptions. On some missions, the teams had to deploy systems from more remote ports than previously planned. The wave powered propulsion and other platform features that allowed the conservation of power, allowed for a longer mission than originally planned.

WAVE GLIDERS IN THE NORTH SEA

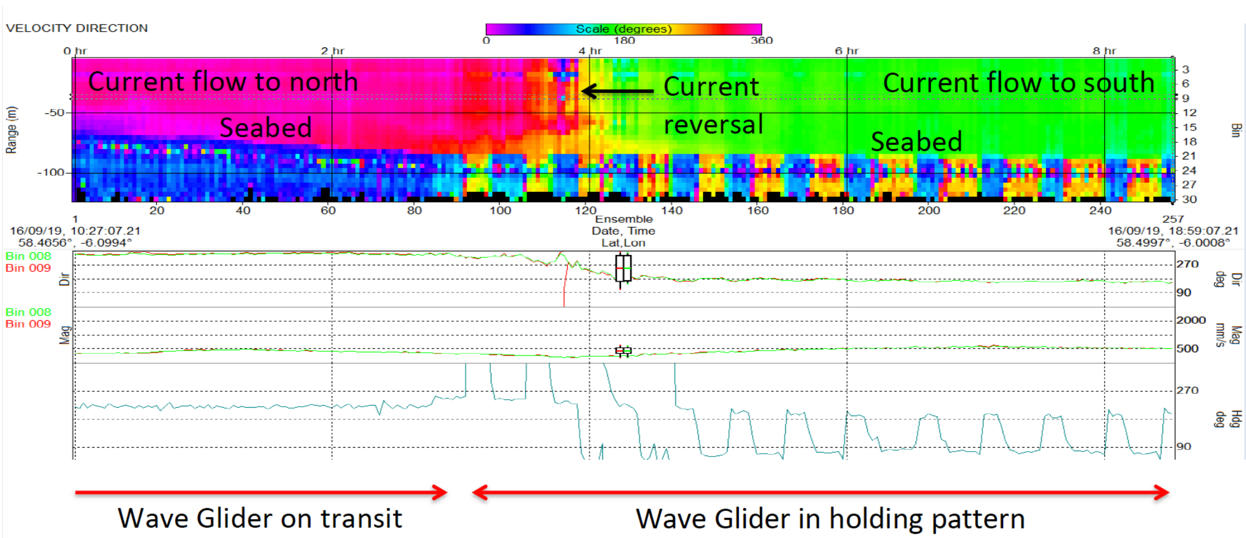
Experience from operations in Arctic and other areas such as the Southern Ocean, have shaped engineering, sensor integration and mission planning efforts. In October 2016, Wave Gliders operated in the heavy sea states of the North Sea in an experiment series called MASSMO 3 (Marine Autonomous Systems in Support of Marine Observations). The MASSMO experiments are run by the UK National Oceanographic Center (NOC) and MASSMO 3 was sponsored by the Defence Science and Technology Laboratory (Dtsl) which aims to ensure that innovative science and technology contribute to the defense and security of the UK. The 2016 exercise involved a fleet of up to 12 submarine gliders and unmanned surface vehicles (USVs) operating off the northwest coast of Scotland in Autumn 2016. The exercise occurred at the same time as the UK's Unmanned Warrior exercise and provided environmental data to support the Royal Navy autonomous system demonstration.

Three Wave Glider systems were deployed (two of the systems were Wave Glider SHARCs on loan from Boeing) with METOC packages that include both ADCP and CTD sensors with the goal of measuring currents, water temperature and salinity to predict local tidal mixing and reversals.

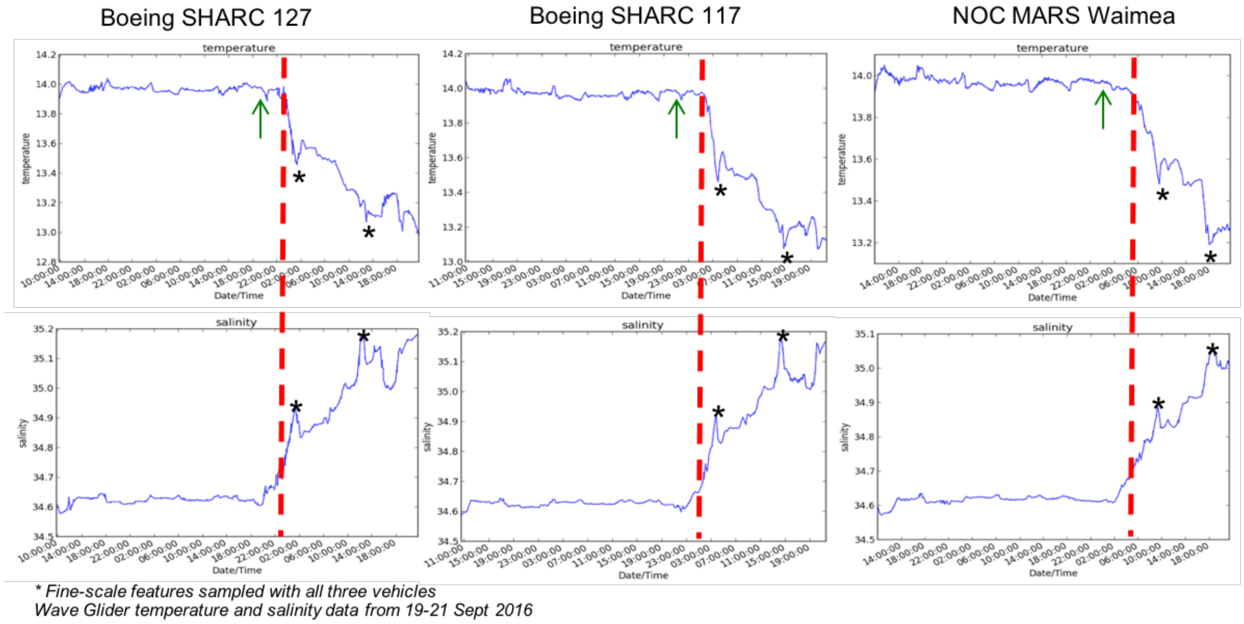
The unique design of the Wave Glider system allowed it to operate in conditions too dangerous and difficult for manned systems and enabled the collection of consistent measurements from multiple vehicles. Key statistics about this mission include:

- 2 x 3 week periods of continuous data collection
- Over 1000 km covered
- Operations up to 140 miles offshore
- METOC data from multiple sensors and vehicles
- Deterministic and dynamic navigation that allowed vehicles to stay on course
- Successful data collection in harsh sea states (7M waves and 60 mph winds)
- Successful detection of tidal current reversals

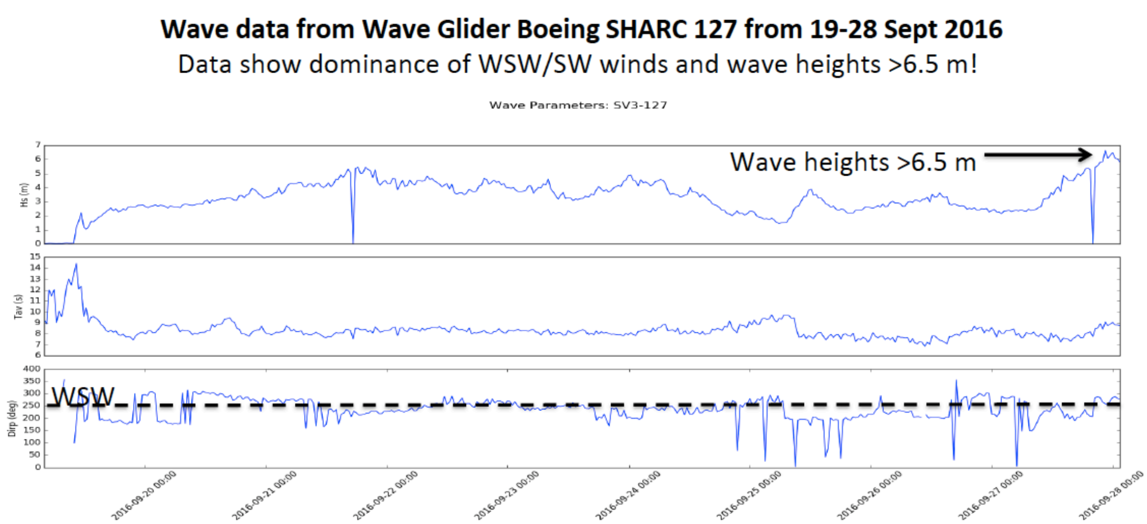
Mission operations were run from Sunnyvale, CA with real-time data shared to multiple teams in the UK. Several pictures help to demonstrate the achievement of data collection goals and the harsh operational conditions.



Wave Glider ADCP data from 19 Sept 2016 – Wave Glider was in northern Minch, arriving on station for shakedown. Data shows clear tidal current reversal and seabed at 60-80m depth. Data courtesy of NOC.



Temperature and salinity data from 19-21 Sept 2016 from multiple Wave Gliders. The temperature and salinity breaks shown were tactically relevant to the military exercise, as well as independent and consistent across multiple vehicles. Data courtesy of NOC.



In situ weather and wave data from Boeing SHARC 127 from 19-28 Sept 2016. Wave heights greater than 6.5m recorded. Data courtesy of NOC.

The ocean is a harsh environment. The key to successful operations in the difficult conditions of the North Sea included:

- Operational risk assessments (ORAs) to define mission goals, risks, and contingencies
- Vehicle design and previous operational experience in rough sea states
- Real-time communication and dynamic navigation (including ship-avoidance)
- Autonomous operations in the event of communication outages
- Field tested sensor integrations and data collection processes

The Wave Gliders deployed on this mission performed well, stayed on course, and managed power per mission plans with no unplanned recoveries.

OTHER MISSIONS

Liquid Robotics continuously collaborates with customers and partners to help them achieve their goals. Global issues that involve Wave Gliders include seismic monitoring for emergency preparedness in the face of natural disasters such as a tsunami, monitoring fish and marine mammal populations and ecosystem health, and curbing illegal fishing.

Tsunami Detection and Alerts

As profiled in a 2017 article in Scientific American,[*] researchers at the Japan Agency for Marine–Earth Science Technology (JAMSTEC) are using a Wave Glider to improve tsunami detection in Japan. Given the many isolated islands and submarine volcanoes surrounding Japan, a network of mobile, tsunami-spotting vehicles could deliver alerts in real-time helping to improve disaster preparedness.

Fish and Marine Mammal Assessment & Tracking

Wave Gliders help researchers track and understand key fish populations around the world. Scientists from Stanford, Duke, and Eastern Carolina University have worked together to monitor tagged Bluefin tuna, striped bass, and sturgeon off the Carolina coast. The value in tracking these species goes beyond learning about their migrations and behavior. It can also help us understand how climate change is impacting our oceans, based on the presence or absence of these fish in different ocean conditions. The rough winter conditions of the Hatteras coastline pose a unique monitoring challenge, withstanding severe weather conditions for long durations, and the Wave Glider helped to fill a critical gap by enabling continuous monitoring.

Illegal Fishing and Marine Protected Environment Monitoring

The estimated total value of current illegal, unreported, and unregulated (IUU) fishing losses worldwide are between $10 billion and $23.5 billion annually.[†] The United Kingdom's Foreign and Commonwealth Office recently used unmanned surface vehicles in conjunction with satellite services to evaluate a more cost-effective approach to monitoring the Pitcairn Islands Marine Reserve. Combining inputs from image, acoustic, and AIS sensors, the Wave Glider demonstrated it could detect suspect vessels using underwater acoustics, visually inspect with an onboard camera, and

---

[*] Harris, Mark. Aquatic Robot Braves Volcanoes and Typhoons to Detect Tsunamis. Scientific American. website. https://www.scientificamerican.com/article/aquatic-robot-braves-volcanoes-and-typhoons-to-detect-tsunamis. January 30,2017. Accessed March 15,2017.

[†] Agnew DJ, Pearce J, Pramod G, et al. Estimating the Worldwide Extent of Illegal Fishing. Sandin SA, ed. *PLoS ONE*. 2009;4(2):e4570. doi:10.1371/journal.pone.0004570

then transmit contact reports and images of these vessels to authorities. This type of intelligence across sensors is critical for reducing data overhead and extending mission capabilities. More exactly, this empowers a country or nation to thoughtfully employ its assets, utilizing a Wave Glider to tip and cue a more expensive system to the area that needs attention.

CONCLUSION

Advancements in technologies, power sources, and the exponential growth of sensors and satellites will be catalysts to help us understand and better address global issues such as dwindling fisheries, energy depletion, and climate change. Unmanned systems in the ocean are maturing quickly and already allow us to remove humans from dull, dirty, and dangerous work. The value of these systems is enhanced when we can send them farther, keep them in operation longer, share data in real-time, and connect them to other platforms or systems. Achieving these goals comes through technical innovation, collaboration, and continuous improvements to operations. For Liquid Robotics, missions in locations such as the Arctic and North Sea have influenced platform design and sensor integration, inspired collaboration, and proven operational capabilities. In the future, the use of unmanned systems in the ocean will move from individual or small deployments of 3-5 systems to larger and more operational deployments that involve multiple systems above and below the sea in continuous operation. The digital revolution that has occurred on land is coming to the ocean – and unmanned surface vehicles will be a critical component to building and enabling that transformation.