Communications relay and autonomous tracking applications for Wave Glider

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***Abstract*—MBARI biological oceanographers make increasing use of mobile autonomous sensor platforms to observe dynamic phenomena, and require near real-time data in order to focus resources on rapidly evolving areas of interest. We have implemented a Wave Glider-based payload called *Hot Spot* that creates a disruption-tolerant communications network between shore and at-sea autonomous platforms. The Hot Spot uses multiple radio and acoustic modems and software to implement a store-and-forward network; the system reliably transfers data between the at-sea Wave Glider Hot Spot, Autonomous Underwater Vehicles (AUV's), benthic instrument packages, and computers on shore. Hot Spot achieves this reliability in an environment where communication links are often unpredictably disrupted. Onboard Hot Spot applications use these capabilities to acoustically determine the location of multiple underwater targets, and can autonomously direct the Wave Glider to follow a moving underwater object. We describe deployments during which Hot Spot quickly transferred science and engineering data between multiple vehicles and shore, and where the Wave Glider used its Hot Spot acoustic tracking application to autonomously follow a moving submerged AUV as part of a large biochemical science campaign.**

Keywords—Wave Glider; communications; DTN; delay-tolerant networking; acoustic tracking

I. INTRODUCTION

In this paper we describe a new Wave Glider-based communication relay system that we call "Hot Spot"; Hot Spot reliably transfers data between shore and at-sea assets that may be submerged or on the surface, and provides a platform for applications that use those capabilities. Hot Spot was developed as part of MBARI's Controlled, Agile, and Novel Observing Network (CANON) project. CANON seeks to achieve a mechanistic understanding of marine microorganism life-cycles, including plankton bloom dynamics [1]. Typical CANON experiments employ multiple propeller driven AUV platforms, buoyancy-driven gliders, drogued drifters, and multiple ships in a coordinated observation effort that includes observations made in the drifting Lagrangian frame. It is important that sensor measurements are available to investigators in near-real-time so that assets like ships and water sampling AUVs can be focused on areas of interest as phenomena develop. As an important CANON component, Hot Spot is designed as a robust operational system to support these science applications.

Autonomous surface vehicles (ASVs) have proven very useful not just as science instrument platforms but also as communication relays. Laske et al [2] describe a broad-band seismometer that can be deployed to the deep-sea floor from a Wave Glider; the Wave Glider then retrieves seismic data through an acoustic link and relays it back to shore via Iridium satellite. McGillvary, Rajan et al [3] describe a sensor network architecture that links mobile underwater, surface and airborne sensors with RF and acoustic links, where data is acquired under autonomous as well as human-in-the-loop control. The Wave Glider plays a critical role as a communications relay between underwater and surface assets in their architecture.

The Liquid Robotics Wave Glider is a particularly attractive platform for our applications. In addition to the technical characteristics described by Manley and Willcox [4], the vehicle is quite versatile and economical to operate compared to crewed surface vessels. The telemetry-relay and acoustic tracking functions we describe in this paper can and have been performed from aboard a crewed ship, but at much greater expense. The daily operational costs of MBARI's 135-foot research vessel *Rachel Carson* are at least fifty times the Wave Glider's operational cost. In addition to dollar cost, we must consider "opportunity cost" - data relay and tracking applications require that a ship or ASV be in a specific region. For example, our Hot Spot Wave Glider recently visited "Ocean Station M", approximately 185 km west of Point Piedras Blancas on California's central coast. The Hot Spot used its acoustic modem to check on two MBARI seafloor assets 4000 m below the surface. Running a ship to and from Station M requires at least 24 hours of transit as well as a day on station. While the Wave Glider took nearly 4 days to arrive on station, minimal human involvement was required. Apart from saving money, a great deal of opportunity cost is saved by freeing up the crewed ship for other tasks better suited to a coastal research vessel.

The Wave Glider's radio relay capability also reduces the cost of AUV operations, as we demonstrate below (Table II). AUVs sometimes come to the surface where satellite or cellular links are feasible for data transfer to shore, but surface time should be minimized since every minute spent on the surface takes time from useful underwater work. AUV radio antennas are generally limited in size and shape, and resulting RF link quality is especially affected by sea-state and vehicle

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buoyancy. Many AUVs are equipped with small Iridium modems and omnidirectional antennas that transfer data to the satellite at 2400 bps and incur airtime costs of about $1.25 per minute or higher. The low transfer rate can result in excessively long surface times and high airtime costs in order to transfer large data sets. Faster and cheaper cellular networks may be utilized in coastal areas, but the small low-profile antennas found on most AUVs are susceptible to link disruption due to wash-over or obstruction by waves.

If the Wave Glider and AUV can arrange to be within radio range of one another when the AUV surfaces, data can be transferred between the two over relatively fast line-of-sight links, reducing the amount of time the AUV must stay on the surface. The Wave Glider can carry larger RF antennas than an AUV, resulting in less wave obstruction, better link quality, and higher bandwidth. The Wave Glider is solar-powered and not as energy-limited as a battery-powered AUV, and can afford the power required to transfer large data sets to shore. Acceptable Wave Glider to AUV range depends on frequency, power, antenna characteristics, and sea state; through experiment we have found it to often be a few hundred meters for 900 MHz and 802.11 radio links, with transfer rates up to several kilobits per second (Table I, III).

II. Design

Hot Spot was directly inspired by the work of K. Rajan at MBARI and of Martins and de Sousa [5], who describe how the sensor network of McGillvary, Rajan et al [3] can be built with the Disruption Tolerant Networking (DTN) protocol. DTN connects multiple RF and acoustic networks, and provides reliable delivery across intermittent long-latency links [6]. While DTN offers many powerful features it became apparent from our tests that the third-party DTN implementation we evaluated was still under development and incompletely documented. The development effort needed to achieve robust DTN operational capability for CANON was judged to be beyond our available resources. Therefore we developed a simpler software architecture based on 'rsync' protocol and implemented mostly with the 'bash' and 'python' scripting languages. Our software runs on a Wave Glider's onboard "Sensor Management Computer" (SMC), utilizing the SMC's Linux operating system and serial ports to communicate with radio and acoustic modems. Our Hot Spot implementation is adequate for CANON's immediate needs, and is robust enough to reliably transport science data over acoustic and radio links within the CANON network.

A. *Modems and antennas*

The Hot Spot acts as an at-sea gateway to the terrestrial Wide Area Network (WAN). Connections to local platforms are made with 900 mHz dedicated direct radio links (for example using FreeWave F series radios), 802.11 WiFi radio links, or with various acoustic communications links for submerged platforms. Other modems on the Hot Spot provide a connection to shore using the Iridium or Globalstar satellite systems (2400 bps or 7800 bps, respectively), or to terrestrial cellular phone networks (greater than 600 Kbit/s). Being the fastest and cheapest shore link, the cellular network is preferred over satellites, but can only be used where cell service is available. When beyond reach of terrestrial cellular phone coverage, the Globalstar satellite network is used for machine-to-machine bulk data transfer within a few hundred kilometers of the coast, and the more reliable (and expensive) Iridium system is used for maintenance and configuration by humans through a console connection, or as a data connection in mid-ocean areas outside of Globalstar coverage.

The Hot Spot design strives to maximize radio performance by mounting radio antennas as high as possible above the waterline (Fig. 1). Local radio link antennas are mounted two meters above the Wave Glider deck to reduce wave occlusion as much as possible, while the satellite and cellular phone antennas are more upward looking and are mounted one meter high. Lightweight carbon fiber masts are used to reduce the weight and windage aloft. The antennas themselves are commercially available from the Antcom Corporation and were selected due to being small, lightweight, and waterproof to 0.25 meters.

Fig. 1. The Wave Glider often gets pulled through the tops of waves by the driving foil, so the radio systems and antennas must withstand being completely submerged.

B. *Software*

Radio communication links between the Wave Glider, AUVs and shore are prone to disruption from multiple causes including sea state and weather, satellite availability, or the Wave Glider moving out of the cell coverage zone. Hot Spot software must reliably transfer data between vehicles and shore in spite of these disruptions and delays. We chose to use 'rsync' protocol as the primary transport mechanism across links that support TCP/IP protocol, including cellular, Globalstar, Iridium, Freewave, and 802.11 WiFi. The rsync protocol [7] offers several advantages:

- rsync is extensively used for file synchronization on today's networks and across the Internet; implementations extremely robust and well-documented, and rsync is included with most Linux distributions.

- rsync's delta-transfer algorithm transfers only the differences between source and destination files, making efficient use of low-bandwidth links.
- rsync works well even on links that are subject to disruption; interrupted file transfers can be resumed where they left off.

In our design, Hot Spot acts as the central computing node of a wireless star network; machines on other vehicles, sensor platforms, and shore act as "endpoints" (Fig. 2). The wireless links connecting the Hot Spot with the endpoints are intermittent; endpoints may submerge or move out of range, sea conditions may vary, etc. All data are transferred by rsync as files, which can contain any kind of data. A file doesn't necessarily contain telemetry, e.g. it may contain commands destined for a particular endpoint. The Hot Spot acts as a store-and-forward node; it pulls files from source endpoints and pushes them to destination endpoints. If a destination link is unavailable, the files remain in the Hot Spot until the link is available. Endpoints play a passive role in transfers; it's the Hot Spot node that initiates rsync pushes and pulls. The Hot Spot can transfer data between any two endpoints, e.g. between two AUVs as well as between an AUV and shore endpoints. The shore endpoint acts as a portal for onshore databases and applications such as MBARI's Ocean Decision Support System, which provides users with a near-real-time view of CANON sensor data as well as the means to issue commands to deployed assets [8].

Each radio-connected endpoint must implement and run the rsync daemon with a specific configuration (port number, password, etc) to be compatible with the Hot Spot rsync daemon. Moreover, the RF link that connects the endpoint must support TCP/IP protocol, which is usually implemented with PPP or SLIP.

As the Hot Spot pulls files from source endpoints, it places the files in its onboard store-and-forward cache. Hot Spot pushes those cached files to their destinations when the link to the destination exists. For every defined endpoint the Hot Spot continually runs 'bash' scripts with the following logic:

```
do forever:
  pull outgoing files from this endpoint, put in local cache
  push cached files destined for this endpoint
  if pull was successful, sync with shore
```

rsync pulls or pushes a file only if the file doesn't yet exist on the destination or if the destination file differs from the source. The Hot Spot continually runs the scripts for an endpoint whether or not the endpoint's link is actually available. When a radio is not powered or not connected to its endpoint, its rsync operations will simply time out and be retried on the next loop. If rsync encounters other errors such as stream corruption, rsync will exit and the operation is retried on the next loop. A file may be partially transferred before an error terminates the transfer; in this case rsync doesn't re-transfer all the data on the next try but instead "picks up where it left off" in the operation. These multiple script instances implement the Hot Spot store and forward capability; even

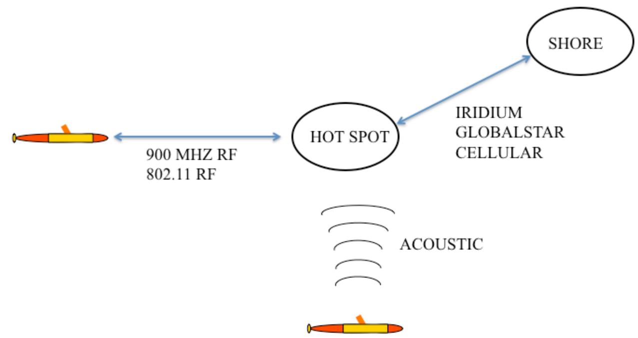

Fig. 2. Hot Spot "star" network

though individual endpoint links come and go, the Hot Spot scripts eventually relay files from sources to destinations.

There are several limitations to our architecture:

- rsync is only supported on TCP/IP links. Acoustic-linked endpoints can participate, but additional "adapter" software must be written for such cases.
- rsync supports point-to-point file copy only, no "fan-out" distribution
- The simple star network precludes multi-hop transfers
- rsync provides file transfer only, no direct support for "remote procedure calls"

Despite these limitations, our design has already proven itself very robust and useful to science operations.

C. *Tests*

In preparing for CANON field campaigns in Monterey Bay we conducted several Wave Glider deployments to plan communication strategies. The Hot Spot's onboard cellular modem was configured to log the received signal strength indicator (RSSI) every 60 seconds. The results show that much of CANON's coastal study area is within cellular phone coverage (Fig. 3).

We also conducted at-sea tests to characterize the 900 MHz Freewave radio link between the Wave Glider Hot Spot and a *Dorado* AUV endpoint. Radios were configured for maximum bandwidth and transmit power. SLIP protocol provided the TCP/IP link over the radios. A test file-set consisting of 27 ascii files and totalling 1.34 MB was "pulled" by rsync from the AUV to the Wave Glider during these tests. During the test, significant wave height ranged from 1.8 to 2.2 meters and wind speed between 11 and 19 kts. The AUV was commanded

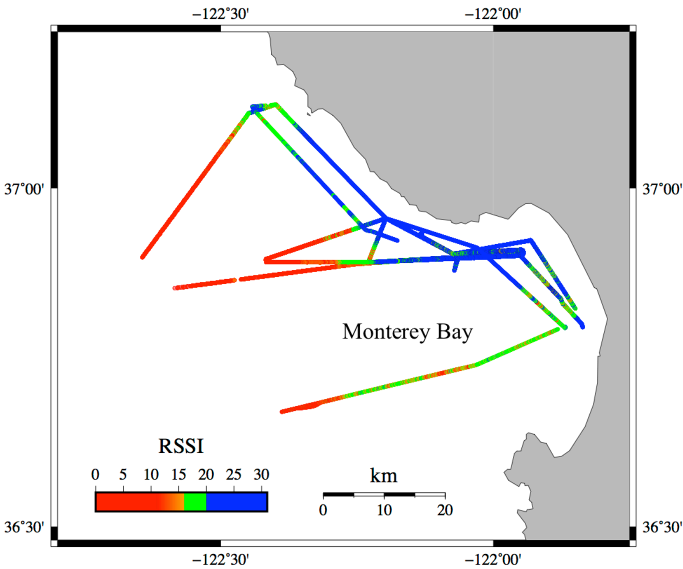

Fig. 3. Received signal strength indicator values from the Verizon cellular network in Monterey Bay, as measured by the cellular modem onboard the Hot Spot Wave Glider. An RSSI of < 10 indicates no service, while > 20 has full performance.

to a series of waypoints at various distances from the Wave Glider, ranging from a few meters to 800 meters. The AUV was allowed to drift on the surface at each waypoint while a test script executed rsync to pull the test file set from the AUV to the Wave Glider. The Wave Glider continually issued ICMP 'pings' to the AUV once every 5 seconds. AUV and Wave Glider positions were also continually logged, allowing us to compute the range between the two vehicles at any given time. Ping packet losses were generally less than 50% out to 400 meters range, and returns were sometimes received at a range of about 800 meters. Note that a successful 'ping' does not guarantee link quality sufficient to support rsync. In all, the test script performed 17 successful rsync "pulls" of the 1.34 MByte test file set from the AUV to the Wave Glider; statistics are shown in Table I.

The test script immediately retries rsync in case of error, and was able to recover the entire file set despite occasional errors. Errors were either "error in rsync protocol data stream" (46% of errors) or "timeout in data send/receive" (54% of errors). Both of these error types are consistent with low RF signal strength, which causes problems for the overlying TCP/IP and rsync protocols.

TABLE I. TRANSFER TIME AND DATA RATE FOR 1.34 MB FILE-SET FROM DORADO TO WAVE GLIDER

range (meters)	**Avg. transfer time for 1.34 MB (minutes)**	**Avg. uncompressed data rate (Kbit/s)**
r = 218 (average)	4.6	38.8
r = 450 (farthest)	8.0	22.3
r < 200	3.2	55.8
200 < r < 450	7.4	24.1

From these results we can compare the cost of Hot Spot transfer to direct transfer from the AUV to shore via Iridium satellite. Assuming a compression ratio of 2.7 for ascii data and 10% disruption overhead due to AUV antenna "washover", the 1.34 MB file set would be transferred through Iridium at 2400 bps in 1819 seconds. If we assume 10 such transfers per day and average Iridium airtime cost of $1.25 per minute, the AUV must spend about five hours on the surface with $380 airtime cost each day. In contrast, on the Hot Spot there is no airtime cost for the 900 MHz link, and the daily Wave Glider operational cost is about $100. The cost of the Hot Spot data transfer to shore depends on whether cellular or Globalstar is used; for cellular the airtime cost for 13.4 MB is about $1, while Globalstar costs $2.58 per MB or $13 for the compressed file set. Overall, Hot Spot data transfer costs are less than 30% of direct Iridium transfer (Table II).

III. APPLICATIONS

Colleagues from the University of Porto's Underwater Systems and Technology Laboratory (LSTS) visited MBARI to participate in the 2013 Fall CANON experiment. They configured their *Xtreme-2 LAUV* ("Light AUV") as a Hot Spot endpoint, using an 802.11 modem for the communication link. Over several days we ran a series of multi-vehicle missions each lasting 6-7 hours during which the Hot Spot relayed messages between the *Xtreme-2*, a *Dorado* AUV (via Freewave radio), and shore (via MultiTech cellular modem using the Verizon cellular network). In a typical scenario, the Hot Spot Wave Glider held position at an agreed-upon location in north Monterey Bay, while the two AUVs acquired upper water column CTD and fluorometer data in the vicinity. The AUVs periodically surfaced within a few hundred meters of the Wave Glider for data transfer. As the data arrived on shore, it was copied into MBARI's Ocean Decision Support System [8] for near-real-time display. We also demonstrated relay of files from one AUV to the other, and transfer of "command files" from shore to the AUVs. Some key statistics for the AUV-to-shore transfers are shown in Table III. The last row in the table shows the effective file transfer rate from AUV to shore, i.e. transfer over the AUV to Hot Spot link and then the Hot Spot to shore link. The rate includes the effects of rsync batch transfers; first the Hot Spot pulls all new files from the AUV, then immediately pushes those files to shore if the shore link is available (the Hot Spot was within the cellular network for nearly all of these transfers.)

In April 2014 the Wave Glider Hot Spot and an MBARI *Long Range AUV* (LRAUV) participated in the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) program off San Pedro Bay near Newport Beach, California [9]. The Hot Spot relayed data between the LRAUV (via 900 MHz Freewave radio) and shore (via Verizon cellular network). A total of 53 MB of science and engineering data were transferred from the LRAUV to shore over 8 days. Additionally, the Hot Spot enabled engineers on shore to access the LRAUV's Linux computer at sea via 'ssh' login over the cellular and Freewave links. This capability allowed the team to solve AUV problems without needing to recover the vehicle, saving considerable money and time.

TABLE II. AUV-TO-SHORE TRANSFER COSTS

	AUV-Iridium direct	AUV-Hot Spot - cell	AUV - Hot Spot - Globalstar
AUV time on surface	5.0 hours	46 minutes	46 minutes
Hot Spot operational cost	N.A.	$100	$100
Airtime cost	$380	$1	$13
Total dollar cost	$380	$101	$113

The Hot Spot participated in a Fall 2014 CANON experiment that utilized simultaneously-deployed Long Range AUVs and ships to measure physical, chemical and biological change within a drifting volume of water over a period of several days. The Wave Glider and AUVs carried sensors to measure conductivity, temperature, backscatter, chlorophyll fluorescence, and dissolved oxygen. The Wave Glider's Hot Spot and one of the LRAUVs we designate as the "Profiler" were equipped with directional acoustic transponders (DAT) that enabled them to determine the range and bearing to a second LRAUV we designate as the "Drifter", which carried an acoustic modem. When deployed, the Drifter used its variable buoyancy system and temperature sensor to maintain its depth at the thermocline (between 30 and 50 meters). The Profiler circled the Drifter at a radius of 1500 meters while performing vertical "yo yos" between 0 and 60 meters, maintaining center on the Drifter by acoustically measuring its range and bearing. Likewise the Wave Glider used its onboard DAT to circle over the Drifter's position at a radius of 50 meters. Thus Drifter, Profiler, and Wave Glider sensors provided a biochemical synoptic view of the center, sides and top of a drifting cylindrical volume of ocean water (Fig. 4). Crewed ships collected samples from this volume each day, using the Wave Glider's surface coordinates to determine the cylinder's location in real-time. The collected samples were later analyzed in the lab with microscopy, genomic methods, and other techniques.

TABLE III. DORADO AND XTREME-2 AUV FILE TRANSFERS TO SHORE

	Dorado AUV (900 MHz)	Xtreme-2 AUV (802.11)
Hot Spot to AUV range (meters)	min 78, max 2489, avg 687	min 56, max 739, avg 314
File size (uncompressed bytes)	min 36, max 40587, avg 14149	min 2190, max 913932, avg 101831
Total AUV to shore time (seconds)	min 14, max 648, avg 182	min 13, max 393, avg 119
Effective AUV to shore transfer rate (bit/s)	min 2, max 7138, avg 1770	min 51, max 224506, avg 15049

Autonomous Wave Glider tracking of the Drifter is accomplished in several steps. A "python" language script aboard the Hot Spot periodically commands the Hot Spot's DAT to send an acoustic ping addressed to the Drifter. The script reads the range and bearing response, converts it to Drifter latitude, longitude and depth, and emails the result to MBARI's shore-side database via cellular modem. A script running on shore processes each incoming result as it arrives and issues a new Wave Glider navigation command specifying the Drifter's latitude and longitude. The command is issued through Liquid Robotics' web services interface, which then sends the command to the Wave Glider using Iridium. In this way the Wave Glider was able to autonomously follow the Drifter AUV for periods exceeding twenty four hours during Fall CANON 2014. Tracking accuracy is subject to communication link delays in the cellular and Iridium links; we observed total measurement-to-navigation execution latencies ranging from roughly two minutes, to over an hour due to a poor cellular link.

IV. FUTURE WORK

We recently updated our Hot Spot's host computer to Liquid Robotics' "Regulus" operating system, which will allow our tracking application to issue navigation commands directly to the vehicle's main onboard computer. This will reduce tracking command latency incurred by our current method of issuing the commands from shore.

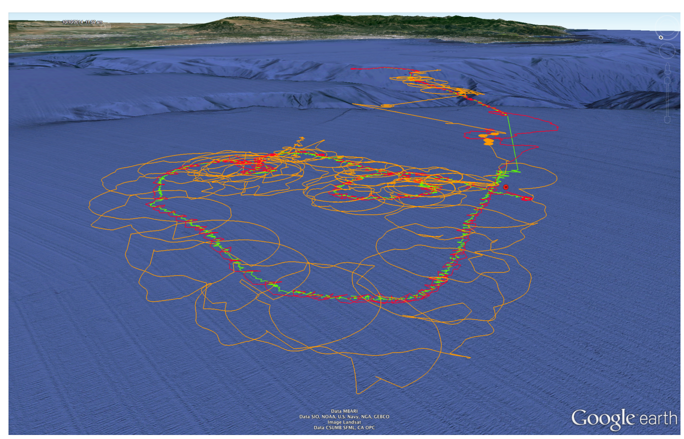

Fig. 4. Tracks of Wave Glider Hot Spot (red), drifting AUV at thermocline (green), and profiling AUV (orange) during Fall CANON 2014.

We expect to make greater use of acoustics in the near future for AUV sensor telemetry as well as vehicle command and control, in order to reduce AUV surfacing time even further. Accordingly we plan to implement automated Hot Spot relay of this data. This could be implemented within the current rsync-based framework through use of software "adapters", or we may revisit DTN as a transport protocol if we can identify a sufficiently robust implementation.

Several Hot Spot functions including radio power management and selection of shore-side link (satellite versus cellular) are performed manually by a shore-based operator using the Hot Spot's Iridium "console". We may automate some of these functions to further reduce operational costs, e.g. software could automatically decide to use a satellite modem if the vehicle is not in a cell coverage area. We will evaluate this and other improvements based on our increasing operational experience.

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