A Communication Framework for Cost-effective Operation of AUVs in Coastal Regions

Arvind Pereira, Hordur Heidarsson, Carl Oberg, David A. Caron, Burton Jones and Gaurav S. Sukhatme

Abstract Autonomous Underwater Vehicles (AUVs) are revolutionizing oceanography. Most high-endurance and long-range AUVs rely on satellite phones as their primary communications interface during missions for data/command telemetry due to its global coverage. Satellite phone (*e.g.,* Iridium) expenses can make up a significant portion of an AUV's operating budget during long missions. Slocum gliders are a type of AUV that provide unprecedented longevity in scientific missions for data collection. Here we describe a minimally-intrusive modification to the existing hardware and an accompanying software system that provides an alternative robust disruption-tolerant communications framework enabling cost-effective glider operation in *coastal regions*. Our framework is specifically designed to address multiple-AUV operations in a region covered by multiple networked base-stations equipped with radio modems. We provide a system overview and preliminary evaluation results from three field deployments using a glider. We believe that this framework can be extended to reduce operational costs for other AUVs during coastal operations.

1 Introduction and Motivation

Autonomous Underwater Vehicles (AUVs) are revolutionizing oceanography. They have been widely used for *in-situ* measurements which would be difficult, expensive, and, in some cases, impossible to obtain by using traditional ship-based sam-

Arvind Pereira, Carl Oberg and Gaurav S. Sukhatme
Dept. of Computer Science, University of Southern California, Los Angeles e-mail: [menezesp,gaurav]@usc.edu

Hordur Heidarsson,
Dept. of Electrical Engineering, University of Southern California, Los Angeles e-mail: heidarss@usc.edu

David A. Caron and Burton H. Jones
Dept. of Biological Sciences, University of Southern California, Los Angeles e-mail: [dcaron,bjones]@usc.edu

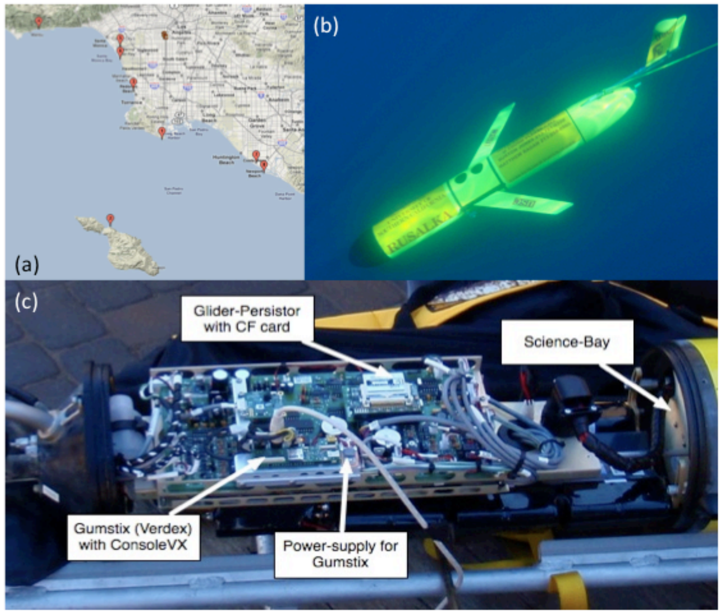

Fig. 1: (a) Basestation locations (current and planned) surrounding the Southern California Bight (SCB), (b) The Slocum glider, (c) Hardware modifications to the glider

pling techniques [1]. AUVs typically use thrusters, rudders and fins as actuators [5]. *Gliders* [6, 3] are specialized AUVs that rely on buoyancy control and shifting center of mass for propulsion, to *fly* in the ocean - an energy-efficient technique that results in long mission times (3-4 weeks) at sea.

Table 1 shows several popular AUV platforms, and their primary modes of communication. The usual operation of AUVs involves the creation of a mission file during the mission planning stage (onshore). Most of the vehicles in Table 1 use a radio link (WiFi, radio modem) for operator-vehicle communications when the vehicle is near the operator. This typically occurs during the mission upload phase. Once deployed, AUVs typically communicate with a basestation onshore (or on a ship) using an acoustic modem or a satellite phone.

While satellite phones have the advantage of being usable at almost any ocean surface location, they are plagued by very low data-rates (*e.g.,* 2400 bps maximum for Iridium) and high costs for transmitted data or call time. Slow data rates imply longer times spent at the surface for data transfer. This is a safety concern in areas with high marine traffic such as the Southern California Bight (SCB), our region of interest and operation (the SCB is the oceanic region contained within 32°N to 34.5°N and 117°E to 121°E). Satellite phone communications are expensive. We estimate the nominal communication cost for Iridium usage to be approximately

USD 2400 for a 3 week glider mission or approximately half of the total expendible cost of the deployment. Others [6] report their Iridium communications cost to be approximately USD 180/day which translates to approximately USD 3500 for a 3 week mission for a single glider. These limitations imply that during a surfacing, experimenters using satellite phones are often forced to transmit subsets of data from the AUV, instead of the entire dataset.

Table 1: AUVs

Name	Manufacturer	Endurance	Radio	Acoustic	Satellite
Bluefin-12	Bluefin Robotics	10-23 h	Yes	Yes	Yes
HUGIN 1000	Kongsberg	17-24 h	WiFi	Yes	Yes
REMUS 600	Hydroid	20-45 h	WiFi	Yes	Yes
Gavia	Hafmynd	24 h	WiFi	Yes	Yes
SAUV II	Falmouth Scientific	Unlimited	Yes	Yes	Yes
Slocum Electric Glider	Webb	4 weeks	Yes	No	Yes
Spray Glider	UCSD	months	No	No	Yes
Seaglider	iRobot	months	No	No	Yes

One strategy to mitigate the shortcomings of satellite phones is to use acoustic modems [9, 4, 2] or combined acoustic/optical strategies [8]. The obvious advantage is that AUVs need not surface to communicate if they are using acoustic modems. However, data rates on acoustic systems are typically low, they also have a high one-time cost and suffer from multi-path interference in shallower coastal regions. Optical techniques are typically shorter range and unsuitable for operations in deeper waters.

We remark that radio modems (*e.g.,* the Freewave^{TM}) used on AUVs (*e.g.,* the Webb Slocum glider (Table 1)) are rated for a range of 60 miles line-of-sight. Their use need not be restricted to dockside operations for mission upload; it could be extended to large near-coastal regions (*e.g.,* the SCB). A multi-AUV deployment over an extended time period in a region as large as the SCB could see significant cost reductions if the primary mode of communication with the AUV was a radio modem instead of a satellite phone. Our experimental platform, the Webb Slocum Glider, is primarily designed to communicate using a Iridium satellite modem during missions. When the operator is within Freewave range, the modem is typically used for launch, retrieval, data transfer, and maintenance of the vessel. In the course of a typical mission, the Freewave is used infrequently, and mostly at the dockside. This is because its effective range to the operator is rather small since it is rare to obtain line-of-sight connectivity between vehicle and operator during a mission due to occlusion.

Can the effective range of the radio modem be extended so that a region the size of the SCB would be effectively 'covered' thus rarely necessitating the use of a satellite phone for operator-AUV operations ? Here we report on the encouraging progress towards answering this question in the affirmative by 1. designing and augmenting coastal communication infrastructure (radio modems onshore at elevated sites for better line of sight connectivity to the vehicles), and 2. designing, implementing and testing protocols for data-transfer using radio modems.

To exploit the radio modem to its fullest potential we make the observation that the Southern California region has several HF-Radar (CODAR) sites at elevated locations. These provide accurate ocean surface current data, and are always instrumented with an internet connection. This infrastructure is a cost effective way to set up a network of radio modem shore stations to provide radio modem connectivity to vehicles on near-coastal missions. Elevated locations provide greater line-of-sight with the vehicle.

We contend that with a minimal modification of the vehicles and a small addition to existing shore locations it is possible to build a network of this kind that scales with multiple vehicles at limited cost. This paper describes the design and implementation of such a system. We report on communication tests using Webb Slocum gliders in the SCB, with the expectation that this strategy can pave the way for a similar use of a reduction in the communication costs for coastal operation of other AUVs.

2 The Webb Slocum Glider Communications System

The glider is a specialized robot driven by buoyancy which can fly in the ocean for extended periods of time at the expense of speed and maneuverability. Glider designers have devoted significant effort to power consumption minimization. The glider's navigation and communications are handled by a low-power micro-controller called the *Persistor*™. This computer performs standard navigational tasks and runs a modified version of PicoDOS™called GliderDOS™which contains glider-specific software.

In normal glider operations, the glider's Freewave modem is configured as a *slave* to connect to only a single *master* Freewave modem at the operator's end. The other side runs software from Webb Research called the DockServer™. The glider can also be operated via any terminal client since it provides a human-readable interface via ASCII strings. There is no inherent packetization of data being performed on the glider since it assumes that it is always connected to a single computer via either of its two links (Freewave or Iridium). This situation, coupled with the fact that the Freewave modems do not have a mode of operation which can independently handle hand-offs between modems, means that it is difficult to build a reliable end-to-end system to communicate with a glider without using packetization for the identification of sources and destinations. Any disruption in communication due to loss of a link or a reconnection of the glider via a new link, results in data corruption.

3 System Design

Our system consists of three main components. At the glider level, we have the communications module that handles the radio communications on the glider. At shore, we have the internet connected basestations which have the radio and antenna to communicate with gliders deployed in the ocean. Finally, we have the control server, a central data-aggregation and command/control server. This overall system design, illustrated in Fig.2 adds more high-level control to the glider operations than currently possible which in turn facilitates autonomous re-tasking of the gliders on mission.

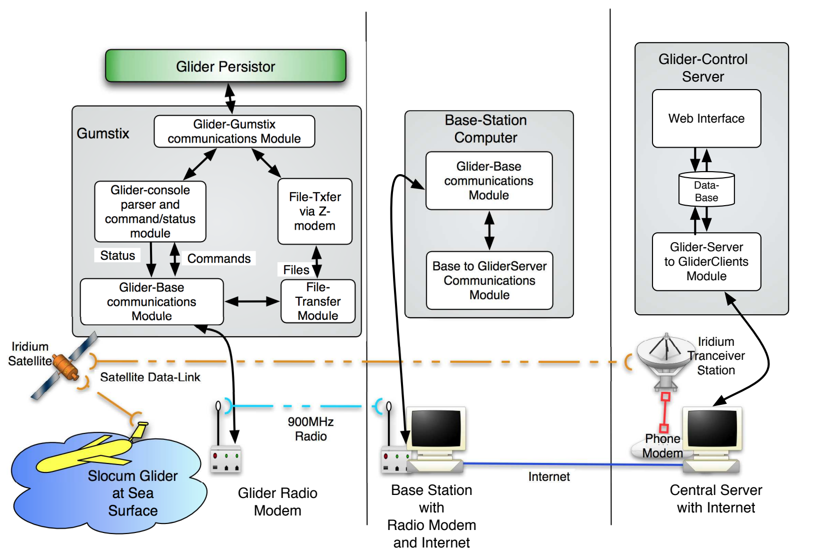

Fig. 2: The System Block Diagram

3.1 *Communication Module and Protocol*

The communications module is a combination of hardware and software to handle communications between the glider and shore. The hardware is specific to the robot platform (in this case a glider), and the software has some general building blocks as well as a platform-specific interface devoted to interaction between the communications code and the control software on the robot itself. We have implemented this module on a Webb Slocum glider, and this paper describes experiments with that particular AUV, but the module can easily be added to most other AUVs.

The basestations and gliders communicate through our own light-weight communication protocol. Each basestation can store and forward certain information between specified nodes (gliders in this case). We treat the Freewave modems as a serial link, and have incoming and outgoing packet queues which provide feedback to vary both the inter-packet delay as well as Freewave packet-sizes. Freewave modems make a "best-effort" delivery attempt on these packets, which can be fragmented into smaller pieces in the event of poor connections. This protocol (which we will describe in more detail in a future paper), also supports guaranteed delivery as well as a non-guaranteed mode of transmission. The packet structure contains 14 bytes without payload data, and allows several applications to multiplex data, such as file transfers, status packets, data packets, terminal commands and so on. We use a *Selective-Acknowledgement* communications scheme with a fixed window which works well in regions with *persistent line-of-sight* between antennae.

On our Slocum gliders, the communication module hardware consists of a Gumstix computer and the aforementioned software. Adding the Gumstix between the glider's control computer and the Freewave is a minimally intrusive way of adding new communication capabilities to the glider. Using a separate computer to interface with a vehicle abstracts the interface between higher-level communications and lower level vehicle control cleanly and can also be used in the future to handle glider re-tasking.We chose a *Gumstix* because, besides its small size, it is a fully functional Linux-based computer, consumes very little power (<120mA @5V), and has good interfacing capabilities. Fig.1(c) shows the physical modifications to the glider due to the addition of the Gumstix. We need to make only 5 modifications to the glider to allow the glider to communicate with an external computer. Although the Gumstix consumes more power than the persistor alone, we have designed the system such that the Gumstix is powered up along with the Freewave modem - a feature that ensures that it gets automatically turned on at the water surface, while staying shut off when the glider is diving.

The platform-specific software on the glider intercepts all messages to and from the glider persistor and the Freewave modem, parses the ASCII strings from the glider and follows the basic control flow displayed in Fig. 3. It also sends necessary status information to shore using our packet protocol, gathers sensor data files from the persistor, compresses them and sends them to the shore station. If communication with the main server via Freewave is unavailable, the glider falls back to Iridium to call in.

3.2 Base Stations

The basestations are the shore stations that handle direct communication with the gliders. The hardware consists of an internet-connected computer, running Ubuntu Linux Server, a Freewave radio and an antenna. The computer runs our communication software which essentially relays datagrams between the gliders and the control server. Communications between these basestations and the control server take place via TCP/IP. If the basestation loses connection to the control server it turns of its Freewave to ensure gliders connect to another basestation or fall back to Iridium for communication.

3.3 Control Server

The control server is the orchestrator of the overall system. It is written in C++ and runs on Ubuntu Linux Server and utilizes a MySQL database for storing data. It

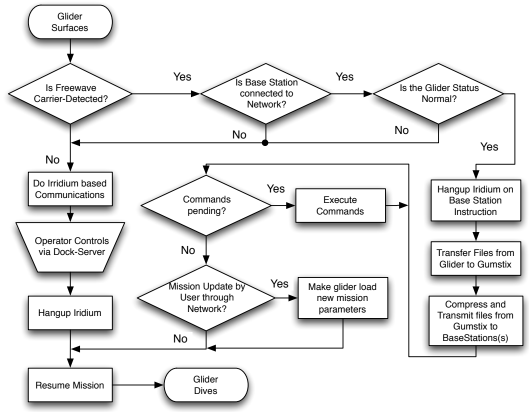

Fig. 3: Control Flow of tasks performed during glider surfacings

maintains a connection to each of the basestations, keeps track of the state of the system and is in charge of issuing commands to connected gliders. It also notifies the end users of events via email. All data it receives is logged to a database. On top of the control server, we have a web based user interface, written in Java^{TM}with Google Web Toolkit, to provide easy accessible control and visualization to the end user of the system. The server also runs 3rd party monitoring software to monitor the health of the basestation computers and software. If a problem is encountered system administrators are notified.

4 Experiments and Results

To test our design, we have performed 3 experimental deployments. The first was off the coast of Santa Catalina Island in November 2008. The other two were near Pt. Fermin in January and February 2009. The heat-map for File transfers (Fig. 4) is based on results extrapolated from glider surfacing and transferring files to shore from locations C, D and E. The heat-map for Carrier Detect (Fig.5(a)) shows a percentage of time the base-stations had Carrier-detect with the gliders to the total time of a surfacing. This metric is based on 4 surfacings. Fig. 5(b) shows a heat-map based on the percentage of protocol-level Link States to the total Carrier-detect duration during a given surfacing. This metric gives us an idea of how well our protocol is performing in real conditions. Observations show that during intermittent communicatios, such as those at C and D, the protocol-link suffers.

5 Conclusion

This paper outlined the design behind a communication system using long-range RF-modems, to communicate with AUVs in a coastal area. Field trials using Slocum

Table 2: Results from Field and Laboratory Tests

Test	Maximum Distance [km]	Data Rate Rate	File Transfers	Freewave Switching	Quality of Link
A - Pt.Fermin *	2.6	Not Measured	Not Tested	No	Poor
B - Pt.Fermin *	5.2	Not Measured	Not Tested	No	Poor
C - Pt.Fermin †	12.3	Not Measured	Not Tested	Yes	Intermittent
D - Pt.Fermin +	9.2	153.5bytes/sec	Yes	No	Slow
E - Pt.Fermin	3.5	1.46KB/sec	Yes	No	V.Good
L - Lab Tests	N.A.	7.883KB/sec	Yes	No	V.Good

* This test was conducted with a faulty antenna installation at Pt.Fermin
† Connection was made to both Pt. Fermin and Catalina Island. Distance to Catalina was 20 km.
+ Remote operator performed a glider re-tasking via network at this location through Pt.Fermin

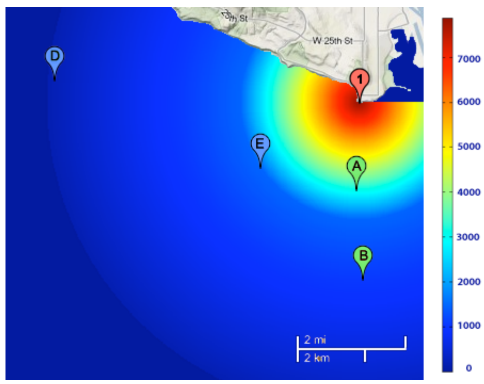

Fig. 4: File Transfer data rate off Pt. Fermin

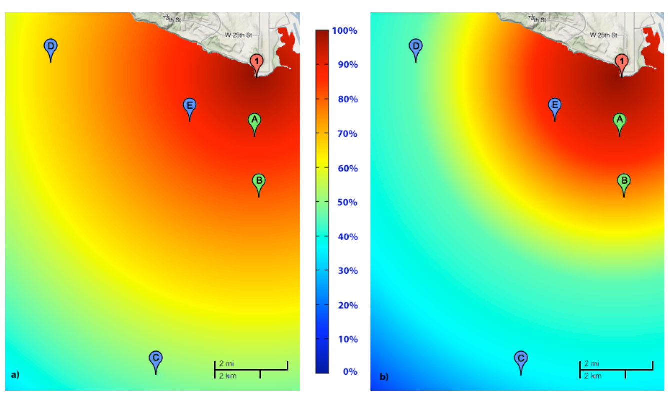

Fig. 5: a) Carrier-detect success percentage (CD on time/Total time) b) Link-Layer protocol's uptime percentage (Protocol time/CD on time)

gliders indicate promising results and give us valuable insights into improvements in the design. On the gliders themselves, we add a small computer to interface between the original glider computer and its Freewave modem. Our communications protocol supports datagrams with priority, can maintain in-sequence transmissions,and has both reliable and un-acknowledged datagram modes. Instead of transmitting all the data from the glider, we create status packets which contain a snapshot of the gliders state by parsing its lengthy ASCII transmission. We also utilize the Gumstix's processing power to compress data files before transmission, which provides us with a typical space saving of approximately 4x. The high data rates our system achieves in the field (1.46KB/sec) is 6 times faster than Iridium while simultaneously transmitting multiplexed glider console information and status packets. This combined speed increase translates to a 24x improvement, which allows us to send more data, while also reducing surface times and cutting down on Iridium data-transfer costs.

Fig. 4, a sparsely interpolated map based on only 3 averaged measurements, implies that fairly high throughputs are possible close to a base-station (<4km), with a fairly sharp bit-rate drop from 1.46KB/s to approximately 154bytes/sec. This significant drop is due to the links becoming more intermittent as carrier detect on the radio is only available 65% of the time at a distance of 9.2km, while it is more than 86.7% at 3.5km. The measurements of communication performance we present here are sparse and were collected at four surfacing locations, but they represent characteristic portions of a typical coastal belt that needs coverage. Field tests have shown that our system allows status packets to be reliably transmitted from distances upto 20km (Glider Surfacing C). We have successfully performed glider re-tasking via the network from a distance of 9.2km - a feature we will use in the future to enable mission re-planning based on data gathered by the glider. We have also developed a central server which allows us to easily collect and visualize data from the glider, or create and send new mission files through the network.

6 Future Work

Experimental results while promising, show that there is room for improvement. From Fig.5 (a) and (b) we make the observation that we can improve upon our protocol, such that its link spans all the time the radio has carrier. We understand that this is a consequence of protocol choices, which were tuned to obtain good results at the lab - which as observed, is significantly different from conditions in the field. We believe local conditions due to waves play a major role in causing communications disruptions, since the antenna of the Slocum glider is very close to the waters surface and local waves occlude line-of-sight between radios. We believe that by using better queue management, introducing variations of re-transmit time and packet sizes, based on the link state, can lead to significant improvements in ensuring we have a much better protocol-level link between the glider and base-stations. We are also in the process of mapping out the entire region of interest for link quality. Equipped with such a map, we can then design planners which incorporate the knowledge of communication link availability to bias the surfacings of AUVs such that they keep overall operation costs low. Concurrent work [7] in our lab, used Iridium to perform feature tracking based on ocean model predictions for the Southern California Bight region. By using our communication system to perform mission adaptations, we will get a more realistic comparison between cost-savings using it instead of Iridium.

7 Acknowledgements

The authors gratefully acknowledge the help provided by Ivona Cetinic, Matthew Ragan, Ryan Smith, Filippo Arrichiello, Ray Arntz, Kyaa Heller and Martin Getrich in the course of the experimental trials, and the support provided by the CINAPS team at USC. This work was supported in part by grants CCR-0120778, CNS-0520305, CNS-0540420 from the US NSF, grant NA05NOS4781228 from the US NOAA, and the Okawa Foundation.

References

1. Elizabeth L. Creed, John Kerfoot, Chhaya Mudgal, and Herve' Barrier. Transition of slocum electric gliders to a sustained operational system. In *OCEANS '04. MTTS/IEEE TECHNO-OCEAN '04*, volume 2, pages 828–833, November 2004.
2. Lee Freitag, Matthew Grund, Sandipa Singh, James Partan, Peter Koski, and Keenan Ball. The whoi micro-modem: An acoustic communications and navigation system for multiple platforms. In *Proceedings of the IEEE Oceans Conference*, 2005.
3. Gwynn Griffiths, Clayton Jones, James Ferguson, and Neil Bose. Undersea gliders. *Feeding and Healing Humans*, 2(2):64–75, 2007.
4. John Heidemann, Wei Ye, Jack Wills, Affan Syed, and Yuan Li. Research challenges and applications for underwater sensor networking. In *Proceedings of the IEEE Wireless Communications and Networking Conference*, pages 228–235, Las Vegas, Nevada, USA, April 2006. IEEE.
5. Jon Erling Gorset Refsnes. *Nonlinear Model-Based Control of Slender Body AUVs*. PhD thesis, Norwegian University of Science and Technology, Department of Marine Technology, Trondheim, Norway, December 2007.
6. Oscar Schofield, Josh Kohut, David Aragon, Elizabeth L. Creed, Josh Graver, Chip Haldeman, John Kerfoot, Hugh Roarty, Clayton Jones, Douglas C. Webb, and Scott Glenn. Slocum gliders: Robust and ready. *Journal of Field Robotics*, 24(6):473–485, 2007.
7. Ryan N. Smith, Yi Chao, Burton H. Jones, David A. Caron, and Gaurav S. Sukhatme. Trajectory design for autonomous underwater vehicles based on ocean model predictions for feature tracking. In *Proceedings of The* 7^{th} *International Conference on Field and Service Robotics*, Cambridge, MA, July 2009. Submitted.
8. Luliu Vasilescu, K. Kotay, Daniela Rus, Matthew Dunbabin, and Peter Corke. Data collection, storage, and retrieval with an underwater sensor network. In *Proceedings of the 3rd international conference on Embedded networked sensor systems*, pages 154–165. ACM, November 2005.
9. Xiaolong Yu. Wireline quality underwater wireless communication using high speed acoustic modems. In *Proceedings of the IEEE Oceans Conference*, 2000.