ACOUSTIC COMMUNICATION NETWORKS FOR DISTRIBUTED AUTONOMOUS UNDERWATER PLATFORMS: PROGRESS REPORT

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Acoustic Communication Networks for
Distributed Autonomous Underwater Platforms
2007-R/RT-2/RCM-21

Progress Report
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M.Stojanovic

Overview

The ultimate goal of this project is to design and develop an experimental platform for testing and evaluation of mobile underwater acoustic networking. This report represents a cumulative summary of research and engineering efforts pursued from the beginning of the project up to this date.

The project has focused on three topics:

1. Design and performance analysis of communication protocols for mobile acoustic networks;
2. Development of the software-defined reconfigurable acoustic modem, and
3. Design and development of a small autonomous underwater vehicle (the micro AUV).

Below, we comment on the work accomplished in each of these areas.

The team consists of the PI, visiting students and research engineers (see list below).

Students:

Arnau Porto Dolc (2006/2007)
Paolo Casari (2006/2007)
Ahmet Turan Ozdemir (2006/2007)
Dylan Owens (2006/2007, 2007/2008, 2008/2009)
Josep Miguel Montana (2007/2008)
Jordi Ribas Oliva (2008/2009)
Francesco Zorzi (2009)

Engineers:

Mehmet Aydinlik (2006/2007)
Victor Polidoro (2006/2007, 2007/2008)
James Morash (2006/2007, 2007/2008)
Justin Eskesen (2006/2007, 2007/2008, 2008/2009)
Michael Soroka (2009)
Dan Soura (2008/2010)

Principal investigators:

M.Stojanovic
Michael Triantafyllou
M.Zorzi

The project has resulted in several publications and Master's theses, which are listed under "References" section of this report (all are enclosed as well).

1. Acoustic communication networking

Several topics were addressed within this area. These topics were addresses from a theoretical standpoint, and range from the fundamental capacity analyses of an acoustic communication system, to the design and performance analysis of specific network protocols for (1) channel sharing and (2) routing.

We have taken an integrated approach to network design that involves cross-coupling on all the layers of the network architecture, from the physical layer (power control) to the medium access control layer (MAC) and the routing layer. In order to provide a proof of theoretical concepts, and verify the performance of the protocols designed, an acoustic network simulator has also been developed (http://seagrant.mit.edu/media/pubs_desc.php?id=1327).

Several students, visiting from the Polytechnic University of Catalonia, Barcelona, Spain, were involved in the research. Jordi Ribas Oliva worked during 2008/2009 on the implementation of physical-layer processes in the software-defined acoustic modem. Josep Miguel Montana, visiting during 2007/2008, was involved in the design and analysis of network protocols. He performed extremely well, completed the M.S. thesis, and published two research papers, one at the Workshop on Wireless Underwater Networks (Wuwnet 2008) and another at the IEEE Oceans Conference 2008. His most recent findings are summarized in a journal paper, submitted to the IEEE Transactions on Wireless Communications. During 2006/2007, Arnau Porto Dolc, a visiting student from the Polytechnic University of Catalonia, Barcelona, and Paolo Casari, a visiting student from the Univerisy of Padova, Italy, worked on the project. Arnau Porto completed his M.S. thesis, and Paolo Casari completed part of his Ph.D. degree thesis, which he has since defended (co-PI M.Zorzi advisor, M.Stojanovic co-advisor). Both students performed very well, and their work was published at the IEEE Oceans Conference 2007. Francesco Zorzi, a Ph.D. student from the University of Padova visited M.Stojanovic at Northeastren University during 2009, working on the problem of energy saving in an underwater acoustic network. That work was ublished at the IEEE Oceans Conference 2010.

The research performed within this area is briefly described below, according to the topics addressed.

(a) **Capacity of a relay acoustic channel**

The work on this topic was presented at the IEEE Oceans Conference 2007 [1]. Below, we quote from the abstract.

Abstract— A relay acoustic link consisting of N hops spanning a fixed distance d is considered. The capacity of the relay link is found to increase with the number of hops as N^{γ}, where γ is a positive constant less than 1. At the same time, the power required to span the link decreases, but because each additional relay introduces a fixed cost, the number of relays in a practical system is limited. Taking this fact into account, an overall cost is defined, based either on a power, or an energy per bit criterion. Minimization of the cost function provides an analytical solution for the optimal number of relays.

The cost of relaying is also evident in the delay, as each relay introduces a delay proportional to the data packet length. However, the distance between relays becomes shorter as more relays are added, thus supporting transmission at a higher rate. Assuming transmission at a rate equal to the channel capacity, the overall link delay is found to behave as $N^{1-\gamma}$. Compared to a situation in which transmission rate is chosen irrespective of the number of relays (a linear increase of the delay with N), rate adjustment offers an improved delay performance.

(b) **Exploiting the bandwidth-distance relationship in underwater acoustic network**

The focus of this work was on highlighting the fundamental differences that exist in an acoustic channel, and taking advantage of the bandwidth-distance relationship in designing reliable message forwarding schemes. This topic formed the basis of Paolo Casari's research at MIT. The results of this work are summarized in [2]. Below, we quote from the abstract.

Abstract—In this paper we study the relationship between effective use of the available bandwidth, energy consumption, and transmission delay in a UnderwaterWireless Acoustic Sensor Network (UWASN). We compare different solutions to transport data to a sink node, namely multihop transmissions through multiple relays and the use of direct relay-to.sink links that require more power but reach the sink in one hop. We also address the effects of different error control policies. Our analysis shows that the energy consumption can be traded off for delay by choosing different policies and by varying some key parameters in each policy.

(c) **Optimizing the transmission range in an underwater acoustic network**

This topic focused on the medium access control (MAC) in underwater acoustic networks, addressing in particular the power consumption and related issues of power saving via power control methods. This work formed the basis of Arnau Porto's work. The results of this research are summarized in a technical paper [3], as well as the Master's thesis [4]. The focus of the work is captured in the abstract below.

Abstract—An extension of Distance-Aware Collision Avoidance Protocol (DACAP) is proposed that permits its implementation in large networks where maximal connectivity is not available. The technique proposed increases the energy efficiency by optimizing the transmission power of the nodes. The optimal power is the minimal power that still guarantees connectivity between each node and the sink. Simulation results show that this transmission power also results in throughput maximization. For a network of nodes uniformly distributed within a rectangular grid, the optimal transmission range can be determined as a function of the node density. A closed form approximation for this dependence is obtained.

(d) **Cognitive spectrum access for underwater acoustic communications**

This topic addressed the limitations of traditional time-division multiple access (TDMA) and frequency-division multiple access (FDMA) in applications to underwater acoustic systems. The results are summarized below in an abstract quotation of a technical paper [5]. This work was lead by the co-PI M.Zorzi, and constitutes part of the continuing research carried out by P.Casari in partial fulfillment of his Ph.D. thesis requirements.

Abstract—While very successful in traditional radio communications, the usage of TDMA and CSMA schemes for underwater acoustic communications is severely limited in efficiency and scalability, primarily due to the very large propagation delays. FDMA seems a viable alternative in that the propagation delay does not impact significantly its efficiency. However, in underwater communications, the capacity achievable on a particular channel depends strongly both on its frequency and on the communication distance, unlike in traditional radio transmissions where FDMA channels usually have comparable performance. Therefore, fixed channel allocation schemes traditionally used for radio FDMA do not perform well in underwater communications. We investigate the application of the principles of cognitive radio and dynamic spectrum access to underwater communications. In particular, we propose a channel allocation scheme which exploits user location knowledge in order to maximize the minimum channel capacity among those achieved by the users. This provides maximum fairness and makes a more efficient use of the available spectrum resources. Performance evaluation carried out by means of simulation shows that our approach can achieve a great improvement in fairness among users, with respect to fixed allocation schemes, while at the same time scaling much better and thus allowing effective communications over larger distances.

(e) **Distributed power control for underwater acoustic networks**

The combined topics of power control and medium access control were addressed as part of the research performed by J.M.Montana and M.Stojanovic. The results of this work are summarized in a technical paper [6], and also in the M.S. thesis [9]. Below, we quote from the abstract.

Abstract—Multi-hop transmission is considered for large coverage area in bandwidth-limited underwater acoustic networks. Discrete power control is introduced as a practical means of optimizing the overall system performance across the physical and the medium access control layers. The required number of power levels and the way in which they are distributed for increasing network densities is analyzed in light of minimum energy per bit consumption.

The system performance is evaluated for different frequency allocation patterns (center frequency fc and bandwidth B). The results show that the total energy per bit consumption can be reduced by moving to higher frequencies, where the background interference is decreased and a greater bandwidth is available. A greater bandwidth supports transmitting at higher bit-rates which has a twofold effect: first, the total energy consumption is reduced because the transmission time is shorter, and second, shorter packets are less likely to collide. These facts encourage the use of high bit-rates even if the application does not require it. In addition, they motivate a review of the medium access control protocols, whose performance depends on the number of collisions.

Two MAC protocols are considered: the Distance Aware Collision Avoidance Protocol (DACAP), a virtual carrier sense like protocol that completely avoids harmful collisions, and the simple Carrier Sensing ALOHA. Coupled with power control, both protocols are shown to be well-suited for networks containing static as well as mobile nodes, which are not synchronized to a global clock.

(f) **Routing for underwater acoustic networks**

The problem of message routing in an underwater communication network was addressed as an independent topic, but also in view of the findings related to power, bandwidth and channel access control. A new protocol, called the Focused Beam Routing (FBR), was proposed, and shown via computer simulation to perform close to the ideal situation in which all the paths through the network are known a-priori. To aid in the analysis, a simulator was developed. The simulator, based in Python, proved to be an invaluable tool for the acoustic network performance analysis. The complete description of the simulation code, that may serve future students as a "User's Guide," is available over the Internet as the MIT Sea Grant Technical Report [8]. The analytical results of our work on the routing protocol are summarized in the technical paper [7]. The work was performed by J.M.Montana and M.Stojanovic, in collaboration with M.Zorzi. The complete results on the network design can be found in the thesis [9]. The work is captured by the abstract below.

Abstract—Multi-hop transmission is considered for large coverage area in bandwidth-limited underwater acoustic networks. In this paper, we present a scalable routing technique based on location information, and optimized for minimum energy per bit consumption. The protocol is suitable for networks containing both static and mobile nodes, which are not necessarily synchronized to a global clock. A source node should be aware of its own location and the location of its final destination, but not those of other nodes.

The FBR protocol can be defined as a cross-layer approach, in which the routing protocol, the medium access control and the physical layer functionalities are tightly coupled by power control. It can be described as a distributed algorithm, in which a route is dynamically established as the data packet traverses the network towards its final destination. The selection of each relaying node is done at each step of the path after letting suitable candidates propose themselves as relays.

The system performance is measured in terms of energy per bit consumption and average packet end-to-end delay. The results are compared to the ones obtained when following pre-established routes, defined using Dijkstra's algorithm for minimal power consumption. It is shown that the performance achieved by this novel protocol is close to the ideal case, minimizing the impact of having to dynamically discover the routes.

(g) **Cross-layer optimization in underwater acoustic networks**

The work on power control (e) and routing (f) gave a clear indication that the performance of an underwater network is not influenced only by the selection of the protocols, but also by the selection of physical layer parameters, such as carrier frequency. Motivated by this fact, we have conduced an in-depth analysis, whose results have been summarized in a technical paper [13]. The abstract below describes the work on this problem.

Abstract—Path loss in an underwater acoustic channel depends not only on the transmission distance, but also on the signal frequency. As a result, the useful bandwidth decreases with distance, a feature not normally present in terrestrial radio networks. This fact motivates the use of multi-hop communications in an acoustic network, and strongly influences its design, since the *same* set of protocols will exhibit *different* performance when operating in a different frequency range.

We consider multi-hop transmission for large area coverage in acoustic networks, with an eye towards efficient power and bandwidth allocation. Power control is used as a practical means of optimizing the overall performance across the physical, medium access control and routing layers. A geographic routing technique, called the Focused Beam Routing, which requires each node to know only its own location and that of the final destination, is coupled with the Distance Aware Collision Avoidance Protocol, which regulates the channel access.

Results show that the average energy per bit consumption is reduced by adjusting the power, center frequency and bandwidth in accordance with the network node density. Specifically, as the density increases, greater bandwidths offer per-hop energy reduction, as well as a reduced packet collision rate.

(h) **Energy Efficiency in Underwater Networks** [14]

With the power-efficient channel access and routing schemes (g) at hand, the next question that we addressed was that of energy efficiency. Namely, a typical underwater network (e.g. a sensor network that measures a slowly varying physical phenomenon) will consist of nodes that do not transmit often, but rather intermittently and each at a low volume of traffic (the total volume of traffic may still be high). In such a situation., it could be advantageous to allow some nodes to turn off their power and go to sleep so that they can save it for a later time. However, a node is not engaged only in transmitting own traffic, but also in relaying the traffic of others. If a node is asleep, it will not be able to help the neighbors, who will then have to increase the power in order to each the nodes farther away. Hence, there is a trade-off in choosing the number of active nodes, i.e. in choosing a sleeping schedule that could optimize the energy consumption. We have proposed a solution to this problem in Ref.[14], whose abstract is quoted below.

Abstract--Energy-efficiency in underwater networks is a key issue that affects all aspects of network design, from hardware to protocols and applications.In this paper we analyze the impact of node density on the energy consumption in transmission, reception and idle--listening, in a network where nodes follow a duty cycle scheme. We consider the energy performance of the network for different scenarios, where a different number of nodes and different values of the duty cycle are taken into account. We simulate different power settings, showing that there exists an effective network density for which the energy consumption is minimized.

2. Reconfigurable (software-defined) Modem

The work on reconfigurable modem, initially led by Dr. Sozer, was continued under the leadership of Dr. Aydinlik. Since Dr. Aydinlik's departure from MIT in 2007, a full-time replacement has not been made; however, Mr. Dan Soura has provided assistance with the modem development, leveraged by the funds from other projects. The original Texas Instruments DSP platform has been put on hold, while an investigation is being conducted on the possibility to use a different implementation platform based on the Universal Software Radio Pripheral (USRP).

DSP modem

During the time of this project, the Matlab-based software of the DSP modem has been developed to include a decision feedback equalizer (DFE) operating under an adaptive LMS and RLS algorithms, as well as packetizing and initial synchronization. The equalizer also contains an integral phase-locked loop (PLL) which is necessary for the operation in the field. The modem was tested in the MIT tank, and also in a smaller lab tank.

The summary of the modem's current status is given in a technical paper [10], presented at the IEEE Oceans Conference 2008.

Abstract—Underwater acoustic (UWA) multi-user network algorithms can only be fully tested through experimental studies where communication signals are transmitted through a real underwater channel. Reconfigurable UWA modem provides a flexible environment for the testing of different communication algorithms including networking protocols. In this paper we present design, implementation, and testing of a physical layeralgorithm on reconfigurable acoustic modem. This physical layer is very flexible; therefore it can easily be modified in order to be employed for the testing of different UWA networking algorithms.

Dr. Aydinlik has also organized a web site that contains all the relevant information about the rModem. The web site has two parts, one that is open to general public http://seagrantdev.mit.edu/rModem/phpweb/pmwiki.php?n=Main.HomePage [11], and another which is dedicated to internal use.

The DSP modem has also been used by J.Morash, as part of the work performed towards fulfilling the requirements of his M.Eng. thesis. Specifically, he has used two modems, deployed at each end of a lab tank, to transmit images wirelessly through the water. A complete summary of that project can be found in the thesis [12].

Texas Instruments (TI) floating point DSP c6713 is used for reconfigurable modem. Two different development boards exist for this DSP. One board is commercial off-the-shelf board from TI called ***c6713 DSK***. The other board is called ***rModem custom board***. rModem custom board has been designed and developed by MIT Sea Grant.

The custom board has many advantages over c6713 DSK due to the features designed specifically for underwater acoustic communications. These features include four ADC/DAC channels, amplifier and FPGA. On the other hand, c6713 DSK board comes at a much lower cost than rModem custom board. Also MathWorks - Simulink has a library for C6713 DSK. This Simulink library makes the development easier for c6713 DSK.

The current status is outlined below for two different development boards.

Off-the-shelf board

The development of a Simulink Real-Time Workshop library for this board has been completed. The library currently includes the following blocks:

1.Serial port receiver and transmitter blocks: These blocks are used to configure the serial port on the serial port daughter car
2.Amplifier control block: This block configures the amplifier
3.Fixed step LMS DFE equalizer with PL
4.Variable step LMS DFE equalizer with PL
5.RLS DFE equalizer with PLL

It should be noted that serial port and amplifier control blocks given in number one and two can only be used on C6713 DSK; however, all equalizer blocks can also be used on rModem custom board.

An amplifier daughter card to drive acoustic transducers has been developed. The block given in number two in the above list is used to configure the amplifier for transmission or reception mode.

Ttransmitter and receiver for c6713 DSK have been tested in the test water tank in the lab. The following parameters were used:

-Frame size: 500. These 500 bits include 200 training bits and 300 data bits
-Frame rate is 1.85 Frame/second
-QPSK modulation
-RLS DFE equalization.
-Convolutional channel coding with Viterbi decoding algorithm,

<u>Custom board</u>

The development of the following Simulink real-time workshop blocks for this board has been completed:

1.Target preferences block: This block is used to configure real-time-workshop for the code generation on the custom board.
2.ADC and DAC blocks: These blocks are used to configure ADC and DAC peripherals. It is currently possible to configure only one channel.
3.Serial port transmit and receive blocks: These blocks are used to configure the serial port
4.Led block: This block is used to turn on/off the leds on the board

USAP

During the recent years, many advancements have been made in the area of software-defined radio communications. These advancements include the development of a freely-available GNU software, that can be used in conjunction with the FPGA-based universal software radio peripheral (USRP) family of products, see http://www.ettus.com/.

We are currently investigating the possibility to use this platform as a basis for the implementation of our software-defined acoustic modem. Several USRP boards have been purchased, and initial developments have been made by Justin Eksesen and Dan Soura. I particular, they have configured the equipment to perform the task of acoustic data acquisition. Dan Soura worked with the USRP board, to bypass its radio peripheral, making the electrical signal drive the acoustic transducer. Effectlively, this has become a Universal Software Acoustic Pripheral (USAP). Initial tests, performed only with the data acquicition function, showed success in recording broadband acoustical signals received on a hydrophone. These signals are automatically converted into wave files, for subsequent off-line processing. A series of tests with experimental data recorded in this fashion has demonstrated success. Jordi Ribas Oliva wirked on implementing the orthogonal frequency division multiplexing (OFDM) modulation/detection techniques in Matlab (as part of a separately funded project) and used these techniques in conjunction with the USAP based data acquisition. The next phase of our work should target porting of the modulation/detection code onto the USAP for a real-time implementation. Most likely, the FPGA cmponents alone will not suffice, and additional DSP components will be used as well.

3. Micro AUV

The work on the small AUV has commenced under the lead engineer Victor Polidoro. Victor has left the MIT Sea Grant in June 2008. Our current lead engineer for this work is Michael Soroka, whose report is included below.

Significant progress has been made with the Micro AUV. Numerous deployments have been executed successfully, both locally controlled as well as remote, proving the vehicle design an overall success. These deployments identified many upgrades which could lead to a better design for the remainder of the Micro AUVs, which have been successfully implemented in Rex 2, the second and improved design of the Micro AUV.

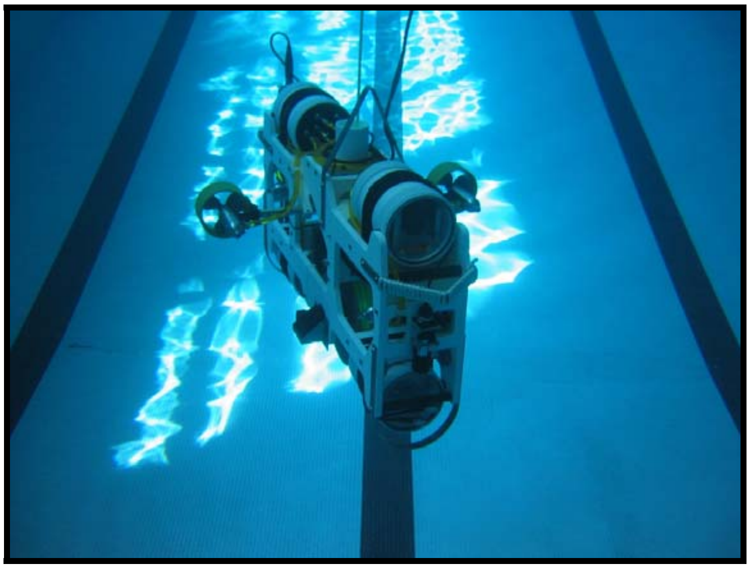

Figure 1 – Rex 1, Micro AUV #1, operating in a pool at MIT

Rex 2 is both smaller and lighter, improving the initial design from two men deployable to one. This weight savings was achieved through several complete system redesigns including the pressure housing assembly and the actuators. The original design called for four independent pressure housings, one for each subsystem (power, computers, motor control, and sensors). The new design uses only one housing, custom designed for electrical and mechanical layout efficiency, eliminating the weight of the housing to housing cabling and associated hardware and connectors. This change also allowed for the reduction in size of all three dimensions, reducing the total volume of material on the vehicle. During this reconfiguration, most of the metal included in the original design was removed as well. The original vehicle control scheme was to control three degrees of freedom (yaw, surge, and sway) on the horizontal plane with four actuators, and the vertical degrees of freedom (heave) with a fifth actuator, the winch. The new control scheme utilizes only three actuators for the same freedom on the horizontal plane, and a lighter and more efficient winch for heave control. This change introduced significant weight savings by eliminating a motor as well as a motor controller, and the batteries required to power this redundant actuator and to overcome the added drag from the fourth thruster.

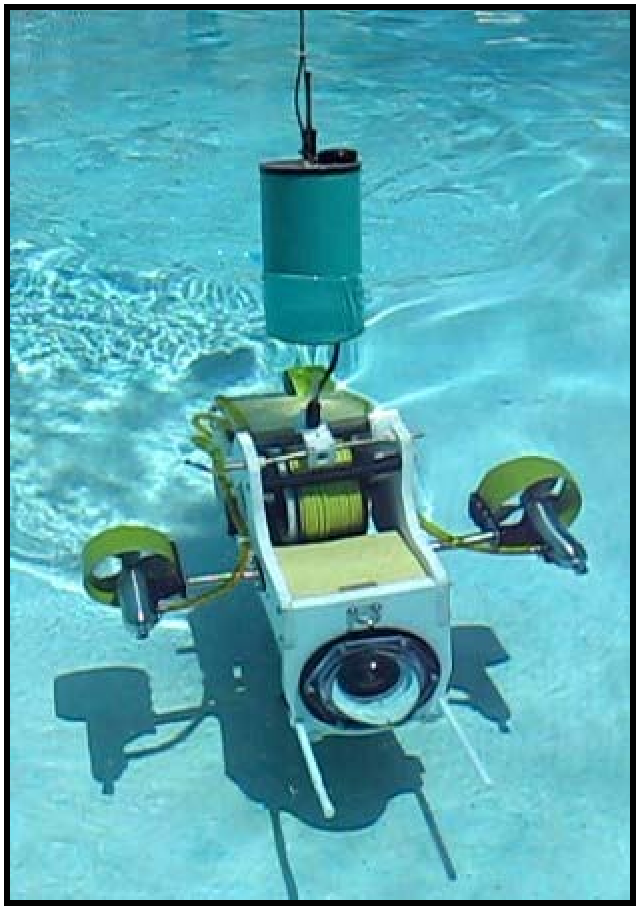

Figure 2 – Rex 2 operating in a pool at MIT. Observe the change in vehicle size between Figure 1 and Figure 2 by comparing the thrusters, which are identical in both vehicles.

Rex 2 has been deployed in many different ocean states ranging from the ideal calm waters of protected bays, to the less ideal water of coastal winter New England with seas ranging from three to five feet. Through all of this Rex has proven to be an excellent vehicle in that it is manageable on the deck of a ship and robust enough to survive harsh conditions and it remains simple to deploy and operate. This leaves little room for improvement in the third iteration of the initial Micro AUV design, Rex 3, which is already in its design phase.

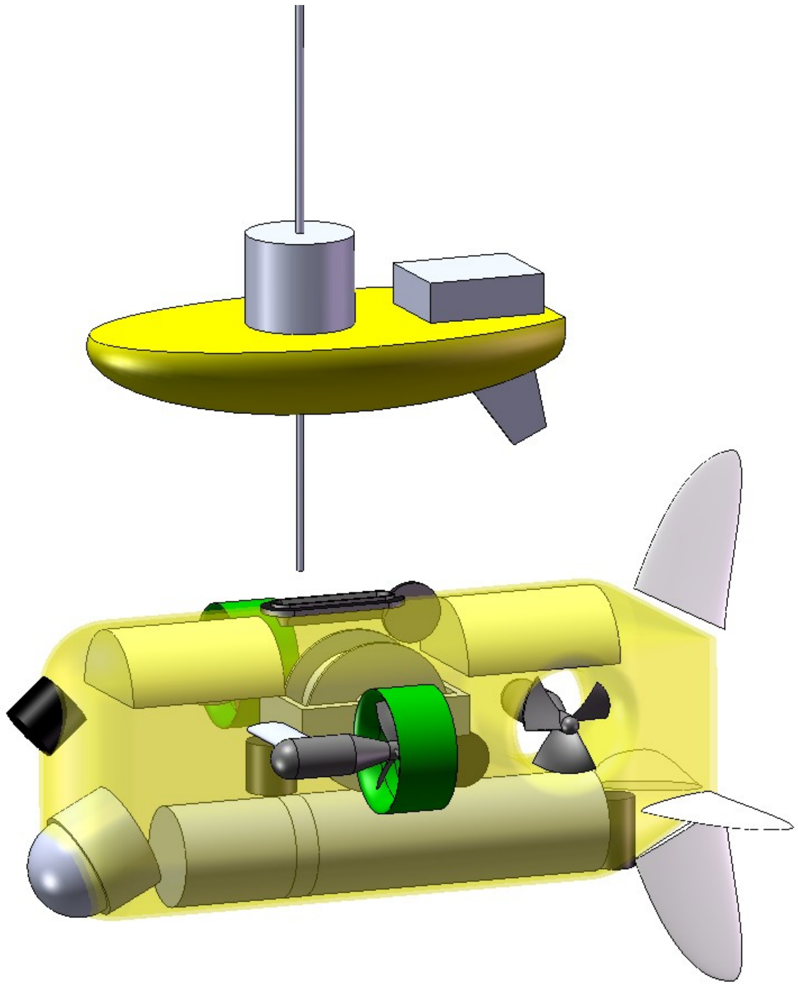

Figure 3 – Proposed Rex 3 design

Rex 3 will be smaller and lighter than both of its predecessors due to a material selection change in the motor assemblies and a lighter more power efficient battery assembly. The vehicle will be shrouded with a hydrodynamic fairing, and equipped with a more hydrodynamic buoy. The tether will be upgraded from the traditional category five Ethernet cable to a Kevlar reinforced 2 millimeter thick fiber optic cable. At its final length, the 100 meter tether will spool to less than three inches in diameter, two thirds that of Rex 2 with only 25 meters of tether, and to less than half the width. The vehicle pressure housing will be deigned to be more space efficient, optimized around the computer, batteries, and modem package.

The next step the AUV lab is in the process of implementing is the installation of the modem package on one or more of the vehicles in our fleet. These modems are already on our primary research submarine, the Odyssey IV, and soon to be on the Rex 2. Communication testing will continue on the Odyssey IV through the end of this fall deployment season, at which point any necessary changes will be implemented on the Rex 2 and Rex 3. These modems will be tested in a variety of ocean waters, and at depth of up to one kilometer.

4. Outreach

The following outreach activities and community service have been undertaken by M.Stojanovic:

1. Journal editing:
-Associate Editor, IEEE Transactions on Signal Processing (since January 2009)
-Associate Editor, IEEE Journal of Oceanic Engineering (since May 2008)
-Editorial Board Member, Elsevier's Phycom (Physical Communciation) Journal (since April 2007)
-Guest Editor for the IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Underwater Wireless Communications and Networks, due last quarter 2008.
-Guest Editor for the IEEE Communications Magazine, Feature topic "Underwater Acoustic Communications," due December 2008.
-Guest Editor for the Elsevier Ad Hoc Networks Journal, Special Issue on Underwater Networks, due 2008.
-Guest Editor for the ACM MC2R Journal, Special Issue on Underwater Sensor Networks, October 2007.

2. Conference organization:
-Chair of the IEEE Ocean Engineering Society Technical Committee for Underwater Communications
-44th Asilomar Conference on Signals and Systems, Session organizer ("Underwater Acoustic MIMO Communications")
-General Chair of the 3rd International Workshop on Wireless Underwater Networks (WUWNet) held in conjunction with the Mobicom conference, San Francisco, CA, 2008.
-TPC co-chair, 1st International Workshop on Wireless Underwater Networks (WUWNet) held in conjunction with the Mobicom conference, Los Angeles, CA, 2006.

3. TPC membership:
-IEEE Oceans Conferences (2006 Asia Pacific, 2007 N.America, 2007 Europe, 2008 N.America, 2009 N.America, 2010 Asia Pacific, 2010 N.America)
-WuwNet (2006, 2007,2008,2009, 2010)
-Fourth IEEE International Conference on Mobile Ad-hoc and Sensor Systems (2007)

3. Outreach publications:
-M.Stojanovic and J.Presig, ``Underwater Acoustic Communication Channels: Propagation Models and Statistical Characterization," IEEE Communications Magazine, January 2009, pp.84-89.
-M.Chitre, S.Shahabodeen and M.Stojanovic, ``Underwater Acoustic Communications and Networking: Recent Advances and Future Challenges," Marine Technology Society Journal," vol.42, No.1, Spring 2008, pp.103-116.
- M.Chitre, S.Shahabudeen, L.Freitag and M.Stojanovic, ``Recent Advances in Underwater Acoustic Communications & Networking," in Proc. IEEE Oceans'08 Conference, Quebec City, Canada, September 2008.

4. Lectures/tutorials (topics in underwater wireless communications/networks):
-IEEE Oceans 2010 Conference Tutorial, Sydney, Australia, May 2010.
-IEEE Underwater Acoustics Signal Processing Workshop, University of Rhode Island, October 2009.
-Plenary talk: International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Perugia, Italy, June 2009.
-NATO Undersea Research Centre (NURC), La Spezia, Italy, March 2009.
-Chief of Naval Operation's Strategic Studies Group Meeting, Boston, MA, December 2008.
-Polytechnic University of Catalonia, Barcelona, Spain, April 2008.
-Northeastern University CDSP Workshop, Boston, MA, March 2008.
-IEEE Communication Society Seminar, Verizon Labs, Waltham, MA, November 2007.

-OFDM Workshop, Santa Clara University, CA, October 2007.
-IEEE Oceans 2007 Conference Tutorial, Vancouver, BC, Canada, October 2007.
-The Water Institute, University of Wisconsin, Milwaukee, May 2007.
-IEEE Asia Pacific Oceans 2006 Conference Tutorial, Singapore, May 2006.
-University of Padova, Italy, April 2006.

5. Short course:
"Underwater Acoustic Communications," University of Padova, spring 2006.

6. Service:
-Administrative Committee Member, IEEE Ocean Engineering Society (elected 2006)
-Steering Committee Member, International Workshops on Underwater Wireless Communications (WUWNet)

6. External Ph.D. committee service:
D.E.Lucani, Massachusetts Institute of Technology, ``Network Coding for Delay Challenged Environments," Ph.D. Thesis, Massachusetts Institute of Technology, February 2010 (M.Medard and M.Stojanovic, advisors)
K.Pelekanakis, ``Bit-interleaved Coded OFDM over Shallow Water Acoustic Communications," Ph.D. Thesis, Massachusetts Institute of Technology, May 2009 (A.Baggeroer, advisor)
E.Page, Polytechnic University of Catalonia, Barcelona, Spain, 2009 (J.Fonollosa, advisor)
J.Guo, University of new South Wales, Australia, 2009 (Dr.Michael Frater, advisor)
M.Chitre, National University of Singapore, 2006 (Dr.John Potter, advisor)

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[9] Josep Miguel Montana, ``Energy Efficient Underwater Acoustic Networks," M.S. Thesis, Technical University of Catalonia, Barcelona, Spain, and Massachusetts Institute of Technology, May 2008, Dr.M.Stojanovic, advisor.

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[12] James P. Morash, ``Implementation of a Wireless Underwater Video Link using a Software-Defined Acoustic Modem," Massachusetts Institute of Technology, Prof. C.Chryssosstomidis and Dr.M.Stojanovic, January 2008, advisors.

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[14] F.Zorzi, M.Stojanovic and M.Zorzi, ``On the Effects of Node Density and Duty Cycle on Energy Efficiency in Underwater Networks," in Proc. IEEE Oceans'10 Asia Pacific Conference, Sydney, Australia, May 2010.