AquaOptical: A Lightweight Device for High-rate Long-range Underwater Point-to-Point Communication

Marek Doniec, Iuliu Vasilescu, Mandar Chitre, Carrick Detweiler,
Matthias Hoffmann-Kuhnt, Daniela Rus

***Abstract*—This paper describes AquaOptical, an underwater optical communication system and compares its communication performance against other underwater acoustic communication systems. We describe AquaOptical's hardware and communication software and discuss experiments. In clear water AquaOptical was tested to achieve a data rate of 1.2Mbit/sec at distances up to 30m. The system was not tested beyond 30m. In water with visibility estimated at 3m AquaOptical achieved communication at data rates of 0.6Mbit/sec at distances up to 9m.**

I. Introduction

We are developing underwater sensor networks [8], [2]. An underwater sensor network integrates computation, communication, sensing, and supporting algorithms. Both hardware and software components of the system have to address the characteristics of the sub-sea environment. Underwater communications have been done traditionally using acoustic communications. Acoustic communications achieve long-distance broadcast at slow data rates with high-power consumption.

In this paper we investigate optical communication as an alternative method for communication underwater. Optical communications underwater have the potential to achieve much higher data transfer rates than an acoustic communication system at significantly lower power consumption, simpler computational complexity, and smaller packaging. However, they operate in a point-to-point communication setting and their range and scope is affected by the water clarity, water light absorption, and power loss due to propagation spherical spreading. We believe that an effective method for uploading large-scale data collected by an underwater sensor network is to use data muling, where a robot equipped with an optical modem will visit each node of the sensor network and upload its data while hovering within optical communication range. In our previous work [10], [8], we have built and demonstrated an underwater sensor network system capable of optical data muling. This paper describes a second generation optical communication system that improves over the previous version in data rate, range, power use, and capability.

Underwater optical communication has been studied by other research groups in the recent past. An early underwater analog communication system was reported in [7]. It uses infrared light to transmit crayfish neuronal activity information from live crayfish in an aquarium. We reported the first use of optical networking underwater in [10], [8], [3], [9]. There are a few recent studies exploring possible techniques and systems for underwater optical comms [1], [4], [6]. Recently the use of waveguide modulated optically lasers has been proposed for high speed optical comms [5]. The device is however directional, very bulky and expensive due to the difficulty in modulating directly green laser at high speed.

This work was supported by DSTA, Singapore. We are grateful for this support.

M. Doniec, I. Vasilescu, C. Detweiler, and D. Rus are with CSAIL, MIT, USA

M. Chitre and M. Hoffmann-Kuhnt are with ARL, NUS, Singapore

II. AquaOptical Hardware

We have developed three optical communication systems: the long range optical modem (called AquaOpticalLong), the short range optical modem (called AquaOpticalShort), and a hybrid optical modem (called AquaOpticalHybrid) that includes the receiver of the short range of the optical modem and the transmitter from the long range optical modem. Our goal with this work is to study the space of designs for optical modems and identify trade-offs in this space. The long range optical modem has been design to operate at low power, distances on the order of tens of meters, and communication rates on the order of 1Mbit/sec. The short range optical modem has been designed to operate at distances on the order of 1-5 meters and data rates on the order of 1Mbit/sec. There are significant hardware and software differences between these modems as described in the next sections. The main trade-off is between cost and distance performance. We also developed a hybrid optical communication modem that uses the lower cost receiver of the short range modem and the more powerful transmitter of the long range optical modem.

A. Long Range Optical Modem

Fig. 1: The receiver and transmitter of AquaOptical.

We have designed and prototyped a long optical communication system called AquaOpticalLong. The system consists of two components, an optical receiver and an optical transmitter,

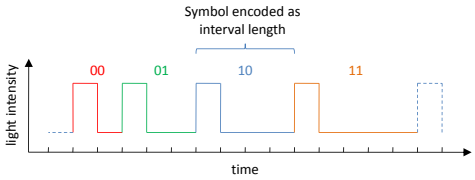


Fig. 2: DPIM (discrete pulse interval modulation): Each bit-pair is represented by a different distance between two succesive light pulses.

each of which are contained in water-tight tubes of 8cm diameter and 35cm length. The transmitter consists of an an array of six 5W LEDs that emit 480nm light. They can be operated at up to 2MHz with a minimum pulse length of 100ns. An FPGA is used to encode a raw data stream into symbols for the physical layer using DPIM (Discrete Pulse Interval Modulation, see Figure 2). Each byte is converted into four symbols, each of which is represented by a different length pulse. The receiver consists of an Avalanche Photodiode which include a low-noise amplifier and is thermo-electrically cooled. The resulting signal is amplified using a variable gain amplifier (VGA). The digitized output is decoded using an FPGA and serialized into a byte stream. The packets are delimited by a fifth symbol whose pulse length is larger than the other symbols used to encode data. Each packet contains a 4 byte header with transmitter address, receiver address, packet length and packet type, and is terminated by a CRC byte. Figure 1 shows the optical modem prototype. This version of the modem does not include error correction.

B. Short Range Optical Modem

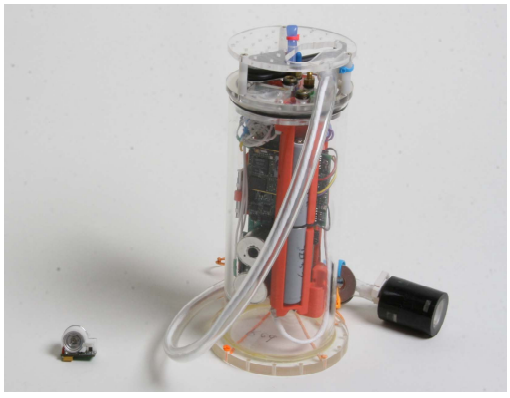


Fig. 3: The receiver and transmitter of AquaOptical can be seen on the left. A sensor node with the short range receiver and transmitter integrated in the top cap is displayed on the right.

The high-level architecture of the short range optical modem is similar to the architecture of the AquaOpticalLong. It includes an optical receiver and an optical transmitter.

The short range receiver uses a commonly available and inexpensive photodiode produced by Advanced Photonix, Inc (part number PDB-C156). The actual sensor of the diode is 8.02mm^2 large and has a response of 14 - 18 A per W of light received. The output of the diode is digitized using an IrDA receiver chip produced by Linear Technology, part number LT1328. The digitized output is decoded using an FPGA and serialized into a byte stream. The packets are delimited by a fifth symbol whose pulse length is larger than the other symbols used to encode data. Each packet contains a 4 byte header with transmitter address, receiver address, packet length and packet type, and is terminated by a a CRC byte.

The short range transmitter consists of one of the units used by the long range optical system, which is a 5W LED that emit 480nm light. An FPGA is used to encode a raw data stream into symbols for the physical layer using DPIM (Discrete Pulse Interval Modulation). Each byte is converted into four symbols, each of which is represented by a different length pulse.

In contrast, the long range receiver uses an array of six LEDs for transmission and an avalanche photodiode which is far more sensitive than the photodiode used in the short range system and much more expensive (US$1200 with the primary control circuitry vs. US$3 for the PDB-C156.) Thus the advantages for the PDB-C156 diode and LT1328 combination are:

- small size (see Figure 3),
- easy to use/control,
- low power consumption,
- low head dissipation,
- and low cost.

Its disadvantages are:

- a worse signal response than the avalanche diode
- and digitization of the signal at an early stage (no LNA, just a preamp) thus loosing possible information.

The advantages for the long range modem are:

- higher sensitivity,
- better amplifiers (this making the detection of very weak pulses possible and increasing communication range.)

The disadvantages are

- size (more than 10 times the volume of the PDB-C156/LT1328 assembly),
- its power consumption (5W for cooling and additional power for control),
- the resultant heat dissipation which requires active cooling and a large heatsink,
- and finally its cost of over US$1K.

C. Hybrid Optical Modem

The hybrid optical modem was designed to enhance the performance of the short range modem by using the more powerful transmitter of the long range system and the lower cost receiver of the short range system.

D. AquaOptical Software

The software of AquaOptical is divided into two parts: the symbol encoder/decoder and the packet encoder/decoder. The symbol encoder is located inside the fpga, the packet encoder

and decoder are runing on the cpu of the sensor node, while the symbol decoder is split between the fpga and the cpu of the sensor node.

The packet encoder takes payload data of 1 - 250 bytes and a destination byte as input. It constructs a valid packet by creating the 4 byte header (source, destination, type, and length) as well as computing and appending the crc byte. It then sends the packet over a serial peripheral interface (SPI) bus to the symbol encoder located inside the fpga.

The symbol encoder receives each packet as a stream of bytes as input. Each byte is split into 4 bit-pairs. The packet is procesed first to last byte. The MSB of each byte are processed first, the LSB last. The packet is started by sending a first light pulse to mark the begining of the packet. A synchronous counter running at 16Mhz is used to time the distances between succesive light pulses to encode the symbols. The duration of the light pulses generated as well as of the different pauses used for the 4 possible symbols can be configured in software.

The symbol decoder front end is running inside the fpga. It takes as input the digitized output of the photo diode. When the first pulse is received, a new decoding cycle is started. A 16Mhz counter is used to time the distance between successive pulses. After each pulse the distance new distance is stored inside a FIFO. If the distance counter exceeds the maximum count (255) then the value 255 is written into the FIFO and the counter simply waits for the next pulse to start.

The actuall decoding of the symbols takes place inside the cpu. The cpu polls the bytes from the fpga using the SPI bus. Each distance is converted into a bit-pair using software configurable threshold values. Every 4 successive bit-pairs are packed into a byte which is written into a buffer. When a distance is read that is larger then a packet timeout threshold then the packet decoder is called to process the current buffer contents.

The packet decoder checks if the crc of the buffer is 0 and if the packet is addressed to this sensor node. It then calls the handler for the data.

The reason that the symbol layer encoder and front end of the decoder are located inside the fpga is so that they can run asynchronously to the cpu and so that packet encoding and decoding is not influenced by other processes that might run on the same cpu.

III. Experiments

We have conducted several experiments in the pool and in the ocean in Singapore Harbor.

A. Pool Experiments

The pool experiments were done in clear water. The optical modem recorded data transmission with 100% success rates at data rates up to 1.2MBit/sec for all the distances tested. In this set of experiments the maximum distance tested was 30m. This limit was imposed by the dimensions of the pool in which we conducted the experiments. We expect good optical communication performance in clear waters at distances up to 50m.

B. Field Experiments in the Ocean

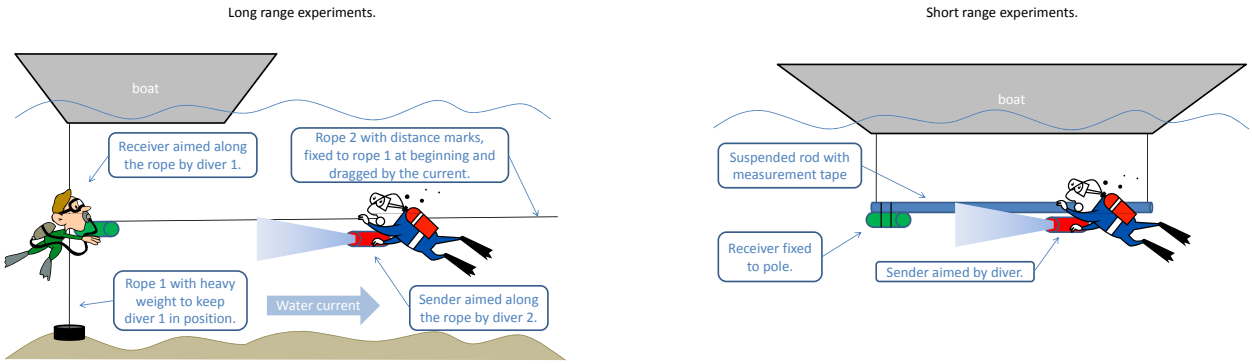
Three sets of field experiments were conducted in the ocean at a location in Singapore Harbor. The big challenge for these experiments was achieving optical communication in low visibility environments. At the experimental site, the water visibility was measured by human divers to be 3m. The goals of these experiments were

1) to measure the success rate of the long range optical modem system at various distances up to 10m.
2) to measure the success rate of the short range optical modem system at various distances up to 3m using blue and green light for comparison
3) to measure the success rate of a hybrid optical modem system consisting of the long range sender and the short range receiver. Since the short range modem system is much less expensive than the long range system such a hybrid configuration might be used for data muling with a robot carrying the long-range receiver and a sensor network with multiple nodes equipped with the short range receiver.

C. Setup

We conducted a suite of experiments to evaluate the performance of the three optical modem systems described in this paper in the ocean. The experiments were conducted near a barge in the Singapore Harbor. The water visibility was measured by human divers at 3m. Figure 4 shows the basic experimental setup for the field evaluations of the optical modems. For the short range experiments we suspended a rigid 4m long rod below the boat at a depth of 4m measured from the top of the water. Prior to submersing the rod, we measured and marked distances on the rod in 50cm increments. Two divers were used in each experiment. One diver carried the transmitter unit and the other carried the receiver unit. The divers were connected to the researchers on the boat using an audio communication system integrated in the diving mask. The receiver was connected to a computer on the boat in order to provide visual feedback about the experiment and debugging information. The diver holding the receiver was instructed to hold the receiver parallel to the rod at position 0. This diver maintained this location for the duration of the experiment. The diver holding the transmitter was given a series of voice instructions. He was first instructed to go to the position marked 1m (which was measured to be 1m away from the fixed receiver) and hold the transmitter parallel to the rod, aimed at the receiver. He maintained this position for one minute and data was collected for 30 seconds at a data rate of 0.6Mbit/sec. The diver was then instructed to move further back in 50cm increments, each time maintaining the transmitter position at the current location for approximately one minute.

A similar experiment was conducted for the long range optical modem. Since our expectation in this case was communication at a much further distance than in the short range evaluations, we used a rope instead of a rod. The rope allowed us to point the receiver and transmitters at each other at



(a) (b)

Fig. 4: Left: Experimental Setup for the Long Range Optical Modem evaluation. Right: Experimental Setup for the Short Range Optical Modem evaluation.

distances greater than what the human eye could see. The rope was kept taught by weights.

D. Short Range Optical Modem Evaluation Data

Specifically, for the short range experiments a single 5 Watt LED was used in the transmitter. Two experiments were conducted, one with a blue LED (470nm) in the transmitter and one with a green LED (530nm). The radiant flux generated by the LEDs is roughly equivalent to 10% of the power input, or 500mW. The receiver uses an off-the-shelf photodiode. The short range experiments were conducted with a throughput of 1.2 MBits or 1.75uS/symbol average.

All experiments were conducted at 4m water depth. For the short range experiments a 4m long pole was suspended off the boat to float horizontally at 4m depth in alignment with the water current. The short range receiver was mounted at one end of the pole and pointed along the pole. It was tethered through a cable to allow for supervision and data logging. A measuring tape was attached to the pole. A diver was holding the transmitter and positioning it at the appropriate distances along the pole. The diver tried at all times to point the modem along the pole. At each recorded distance the diver stayed for at least 20 seconds and continuously pointed the transmitter along the pole towards the receiver. Measurements were taken and binned in 2 second intervals. Each measurement consisted of the number of valid packets received and a histogram of pulse lengths received in that 2 second interval.

Figures 5 and 6 show the experimental data with the short range optical modem using green and blue light. We expected to see blue light outperform the green light as predicted by the literature. However we observed green light to be more effective in the Singapore Harbor. We believe this is due to the water color in the Singapore Harbor.

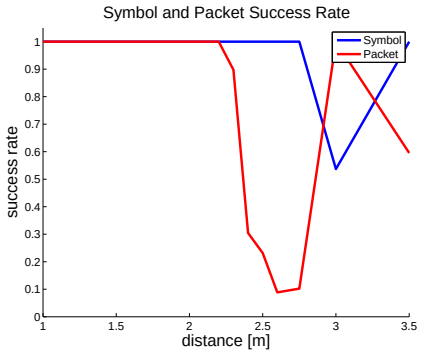


Fig. 5: Singapore Optical Modem Experiment: Short Range symbol and packet success rate using green light. The x axis corresponds to distance. The y axis shows the percentage of valid pulses received (blue line) and valid packets received (red line).

The blue line corresponds to the percentage of valid pulses received (corresponding to a symbol) divided by the total number of pulses received. Bad pulses in the short range receiver are due to ambient noise whereas bad pulses in the long range receiver are due to both ambient noise and noise inside the receiving circuit due to the VGA.

The red line is the number of valid packets received divided

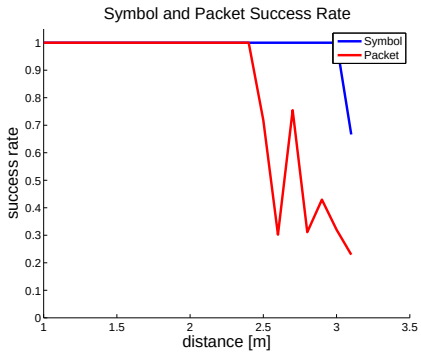


Fig. 6: Singapore Optical Modem Experiment: Short Range symbol and packet success rate using blue light. The x axis corresponds to distance. The y axis shows the percentage of valid pulses received (blue line) and valid packets received (red line).

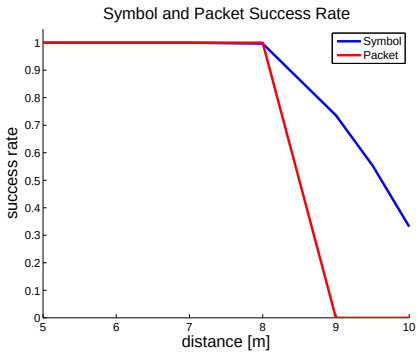


Fig. 7: Singapore Optical Modem Experiment: Long Range symbol and packet success rate using blue light. The x axis corresponds to distance. The y axis shows the percentage of valid pulses received (blue line) and valid packets received (red line).

by the total number of packets received. Packets were 128 bytes long. Valid packets are those addressed correctly and the crc at the end of the packet matches.

E. Long Range Optical Modem Evaluation Data

For the long range experiments six 5 Watt blue (470nm) LEDs were used in the transmitter and an avalanche photodiode with a VGA in the receiver. The radiant flux on the transmitter was 3W. The first day long range experiment was conducted with a throughput of 666 KBits or 3uS/symbol average. The second day long range experiment was conducted with a throughput of 333 KBits or 6uS/symbol average.

The long range experiments were conducted in a similar fashion as the long range experiments. However the 4m pole was replaced with a 12m rope with 1m markings that was tied to the receiver. The other end of the rope was not tethered and was floating in the current (up to 2 m/s). A diver held the receiver and tried to point it along the rope at all time. A second diver held the transmitter and was holding on to the rope while trying to point the transmitter along the rope. The rope was straight at all time due to the strong current pulling the second diver and thus straightening the rope. It was the second divers responsibility to keep a depth of 4m. Measurements were conducted in the same fashion as with the short range receiver.

Figure 7 shows the experimental data with the long range optical modem (using blue light). Figure 8 shows experimental data with the long range optical modem (using blue light) taken on a different day.

The blue line corresponds to the percentage of valid pulses received (corresponding to a symbol) divided by the total number of pulses received. Bad pulses in the short range receiver are due to ambient noise whereas bad pulses in the long range receiver are due to both ambient noise and noise inside the receiving circuit due to the VGA.

The red line is the number of valid packets received divided by the total number of packets received. Packets were 128 bytes long. Valid packets are those addressed correctly and the crc at the end of the packet matches.

F. Hybrid Modem Evaluation Data

During the long to short range experiments we used a short range receiver (off the shelf photodiode) with our long range 3W radiant flux transmitter. The same procedure as in the long range experiment was used in this case.

Figure 9 shows experiments carried out during the second day using the long range optical modem sender and the short range optical modem receiver. The blue line corresponds to the percentage of valid pulses received (corresponding to a symbol) divided by the total number of pulses received. Bad pulses in the short range receiver are due to ambient noise whereas bad pulses in the long range receiver are due to both ambient noise and noise inside the receiving circuit due to the VGA. The red line is the number of valid packets received divided by the total number of packets received. Packets were

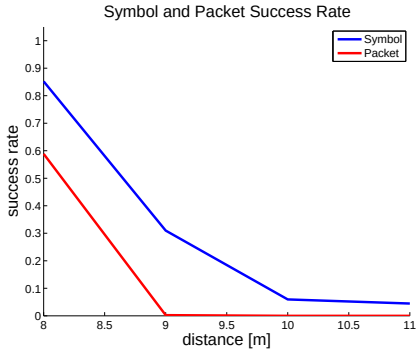


Fig. 8: Singapore Optical Modem Experiment: Long Range symbol and packet success rate using blue light. The x axis corresponds to distance. The y axis shows the percentage of valid pulses received (blue line) and valid packets received (red line).

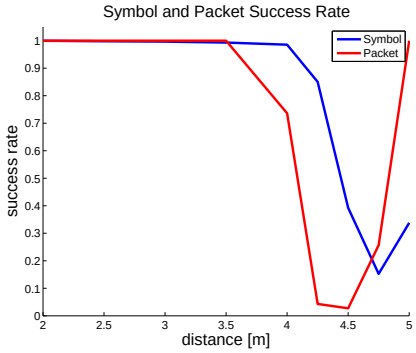


Fig. 9: Singapore Optical Modem Experiment: Hybrid Modem success rates using the long range optical modem sender and the sort range optical modem receiver using blue light. The x axis corresponds to distance. The y axis shows the percentage of valid pulses received (blue line) and valid packets received (red line).

128 bytes long. Valid packets are those addressed correctly and the crc at the end of the packet matches.

G. Discussion

Figure 10 shows the time history on one experiment. We can see how the diver conducting the experiment (in this case Matthias) moved first away and then closer to the sender during the experiment. You can also see a very clear peak where the packets start coming through. The portion of the graph before the peak is noise while the diver moved into position.

For each distance interval the packet and symbol success rate were measured for 30 seconds. The testing rate for the data transfer was 600kbit. Under these harsh visibility conditions, the long range optical modem achieved very close to perfect transmission rates up to 8m. The performance degrades but is still operational up to 9.5m. At 10m the receiver does not pick up any symbols.

These experiments demonstrate that the optical communication system is very well suited for data transfer at large distances (e.g 25m) in clear waters. The data transfer rate was good at twice the visibility range in turbid waters. We believe AquaOptical is an encouraging first step toward creating an effective optical communication system for use in data muling and other underwater data transfer scenarios. Next steps include hardware redesign for power optimization and the development of a software layer capable of error correction and higher-level interfacing to the system.

IV. Conclusion

This paper discussed the design of a family of three underwater optical modem systems. We have designed and built three systems: a long range optical modem, a short range optical modem, and a hybrid modem. We analyzed the trade-offs between these systems and characterized their performance in the pool and in the ocean. Our preliminary experimental results suggest several hardware and software improvements to the system as well as additional experimental characterization. Our current efforts are focused on the software side to include error correction in the symbol processing and on the experimental side to evaluate the sensitivity of the systems to orientation. Next we plan to use the optical modem systems for data transfer between sensor networks equipped with the short range modem transmitter and receiver and a robot equipped with the long range modem transmitter and receiver.

Acknowledgments

This work was supported by DSTA, Singapore. We are grateful for this support. We are also grateful to the team at ARL, National University of Singapore, for providing logistical and technical support for our experiments.

References

[1] Mark Alan Channey. Short range underwater opical communication links. Master's thesis, North Carolina State University, 2005.

[2] C. Detweiller, I. Vasilescu, and D. Rus. An underwater sensor network with dual communications, sensing, and mobility. *OCEANS 2007 - Europe*, pages 1–6, June 2007.

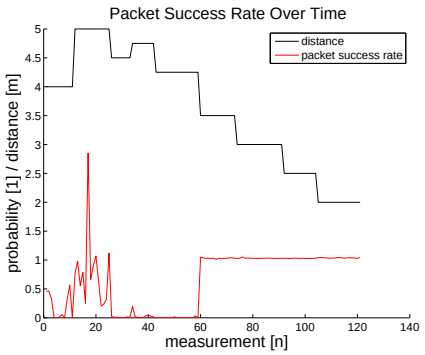


Fig. 10: The timeline of the experiment. The the x axis corresponds to discrete 2 second-long measurements. From left to right we see the history of the experiment. The y axis is the packet success rate (in red) and distance (in black.).

[3] M. Dunbabin, P. Corke, I. Vasilescu, and D. Rus. Data muling over underwater wireless sensor networks using an autonomous underwater vehicle. *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, pages 2091–2098, 15-19, 2006.

[4] J.W. Giles and I.N. Bankman. Underwater optical communications systems. part 2: basic design considerations. *Military Communications Conference, 2005. MILCOM 2005. IEEE*, pages 1700–1705 Vol. 3, Oct. 2005.

[5] Frank Hanson and Stojan Radic. High bandwidth underwater optical communication. *Appl. Opt.*, 47(2):277–283, 2008.

[6] Felix Schill, Uwe R. Zimmer, and Jochen Trumpf. Visible spectrum optical communication and distance sensing for underwater applications. In *AGRA*, 2004.

[7] Y. Tsuchida, Hama N., and Takahata M. An optical telemetry system for underwater recording of electromyogram and neuronal activity from non-tethered crayfish. *J of Neuroscience Methods*, 2004.

[8] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin, and P. Corke. Data collection, storage, and retrieval with an underwater sensor network. In *SenSys '05: Proceedings of the 3rd international conference on Embedded networked sensor systems*, pages 154–165, New York, NY, USA, 2005. ACM.

[9] I. Vasilescu, K. Kotay, D. Rus, L. Overs, P. Sikka, M. Dunbabin, P. Chen, and P. Corke. Krill: An exploration in underwater sensor networks. *Embedded Networked Sensors, 2005. EmNetS-II. The Second IEEE Workshop on*, pages 151–152, May 2005.

[10] I. Vasilescu, P. Varshavskaya, K. Kotay, and D. Rus. Autonomous modular optical underwater robot (amour) design, prototype and feasibility study. *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, pages 1603–1609, April 2005.