AquaNodes: An Underwater Sensor Network

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ABSTRACT

This paper describes an underwater sensor network with dual communication and support for sensing and mobility. The nodes in the system are connected acoustically for broadcast communication using an acoustic modem we developed. For higher point to point communication speed the nodes are networked optically using custom built optical modems. We describe the hardware details of the underwater sensor node and the communication and networking protocols. Finally, we present and discuss the results from experiments with this system.

Categories and Subject Descriptors

B.0 [**Hardware**]: General

General Terms

Design, Experimentation, Performance

Keywords

Acoustic, AquaNode, Network, Sensor, Underwater

1. INTRODUCTION

In this paper we describe the underwater sensor network hardware we designed, built, and deployed in lakes, rivers, and the ocean. The hardware consists of static sensor network nodes and mobile robots that are dually networked optically (for point-to-point transmission at 330kb/s and acoustically for broadcast communication over ranges of hundreds of meters at 300b/s). We discuss the communication performance of the network during experiments with this system. We describe the sensor network hardware, explain the communication protocols, and show results from field experiments.

The sensor nodes are called *AquaNodes* and are shown in Figure 1. These nodes package communication, sensing, and computation in a small cylindrical water-tight container. Each unit includes an acoustic modem and an optical modem implemented using green light. The system of sensor nodes communicates with a TDMA protocol and is self-synchronizing. The system is capable of ranging and has a data rate of 300 b/s verified up to 400 meters in fresh water and in the ocean. The sensors in the unit include temperature, pressure, and camera with inputs for water chemistry sensors.

Because the nodes are light and small, they are easily deployed by manually throwing them overboard. Once deployed, the nodes are anchored with weights and form a static underwater network. This network self-localizes using a range based 3D distributed localization algorithm extension of our 2D distributed localization algorithm developed in [12].

1.1 Related Work

There has been a growing interest in automating oceanographic research applications. This research is motivated by the vision of collaborative oceanographic research projects such as the Autonomous Ocean Sampling Network II [1] and [10, 8, 2, 5]. It is becoming more important for robots and sensing instruments to be able to assist in the deployment of measuring systems or to act as part of large-scale data-collecting networks.

In designing the underwater network system, we draw from important results in acoustic telemetry [4] and the design of sensor networks for aerial operations [11]. We also build on the success of the WHOI acoustic modem [14] to develop a flexible, reprogrammable acoustic model with new capabilities such as reprogrammability, ranging, TDMA communications, and self-synchronization.

2. THE UNDERWATER SENSOR NETWORK

2.1 AquaNode Hardware

In our previous work [13] we described our first underwater sensor network. This network had limited acoustic capabilities. We now describe the second generation underwater sensor network that has retained the original goals addressing them with a different design and enhanced capabilities.

The underwater sensor nodes are called *AquaNodes* (see Figure 1). So far we have built 10 nodes. Each node is build around a CPU unit, based on the ATmega128 processor, with 128kbyte of program flash memory, 4kbyte of RAM, and 512kbyte of external flash memory for data logging/storage. This board has temperature and pressure sensors, and inputs for 6 other 24-bit analog or digital sensors. The underwater sensor node is contained in an acrylic watertight cylindrical container with a radius on 15 cm and height of 25cm. The caps of the tube are molded to fit the electronics that need to be there (e.g. the optical receiver and transmitter, the acoustic transducer, and cables). The bottom cap of the box has a winged system that allows the addition of free-standing measuring devices and provides a suspension mechanism for weights.

Figure 1: A picture of some sensor nodes drying.

The mother board is interfaced to a special optical communications board through a serial link. The optical board has its own processor and uses 532nm light. It is capable of a range of 2.2m/8m[1], within a cone of 90/30 degrees and a maximum data rate of 320kbits/s. Additionally, there is an acoustic communication module using 30kHz FSK modulation and an in-house built transducer with a range tested up to 400m (we believe it can go farther) and a data rate of 330 bits/s.

For sensing, each node has a pressure sensor, temperature sensor, and a 640 × 480 color camera. The sensor node is powered by 56 watt-hours of Lithium Ion batteries. When all the components of the node run at full power (e.g. the communication hardware is fully powered and operates continuously and the all sensors are also fully powered and sample continuously) the battery provides 1-2 weeks of continuous operation. In sleep mode the battery provides 1 year of power. The duty cycle can be adjusted to vary sampling/communication rate versus uptime. The box is weighted to be 20% positively buoyant, and balanced such that if dropped in water it always lands top up.

3. COMMUNICATION

The sensor nodes are networked dually. Optical communication allows line-of-sight fast data transfers at a rate of 320 Kb/s as described in [13]. Optical communication can occur when there is direct line of site within a 90 degree cone with a range of 2 m (extensible to 8m using lenses). The acoustic communication enables broadcast at lower data rates of 330 kbits/s at distances of over 400m.

[1]The 8m range requires lenses on one of the devices and actively pointing it toward to other

The acoustic modem is built around a Analog Device Blackfin BF533 fixed point DSP processor running at 600Mhz. For transmission the processor generates a PWM signal which is amplified by a 10W D class amplifier, operating at about 90% efficiency. The amplifier drives a cylindrical piezoceramic transducer developed in house. For reception, the signal from the same transducer is passed through a band pass filter, and then a variable gain amplifier which drives a 12bit A/D sampling the signal at 250 k samples per second.

The modem uses a FSK modulation on a 30Khz carrier frequency. The symbol size is 3ms, consisting of 1ms transmission and 2ms pause. The numbers were determined experimentally. We aimed to reach a good trade off between inter-symbol interference and frequency resolution on the receiver side. Each data packet consists of a synchronization pulse followed by 16 bytes of data. The synchronization pulse is a linear frequency sweep of 2.2ms recognized on the receiver side by a matched filter. The data consists of 10 bytes of payload, 2 byte CRC, 1 byte for the source ID, 1 byte for the destination ID, 1 byte for the packet type and 1 byte for the slot number (used by the TDMA scheduler).

3.1 A TDMA Protocol

A typical network deployment starts with initializing the number of slots at deployment type. Typically, we start with a number of slots equal to the number of nodes in the system. We can add slots on the fly or at any time over the duration of the network. The additional slots are allocated to support more frequent communication for the moving nodes, or for base stations. Nodes are allocated a slot number at the beginning of deployment. However, any node can send a command to another node to release its time slot.

Our TDMA protocol uses 4 s time slots. Each time slot is divided into a 2 s master packet for the slot owner, and 2 s response time. The response time may be one of two categories, based on the owner's request. The owner may request communication to a single node, or communication to multiple nodes. In the case of communication to a single specific node, the response includes data. However, the response packet is also used to compute the range between the two nodes (e.g., the round-trip time offset by 2 sec.) In the case of multiple destinations, the responses are spaced at 200 ms intervals and are used primarily to compute multiple ranges within one communication slot. This communication modality does not support much data transfer, but it enables a very efficient way of estimating multiple ranges. This feature is important for applications that use the sensor network as an external localization system to localize and track a moving node, for example using the algorithm in [9], as well as for applications that require the network to self-localize and establish a system of coordinates, for example using the algorithm extensions of [12].

In our TDMA implementation, a node can own anywhere between 0 and N time slots. The owners of the slots can be changed dynamically in real time.

3.2 Self-synchronization

A key feature of our sensor network system is the ability of the system to self-synchronize without access to an external clock source such as a GPS or to very high-precision clocks. The self-synchronization algorithm works as follows.

The nodes are initialized with the total number of slots and each node knows its slot number. When node n with allocated slot N is deployed in water, it waits to hear a correct master packet for $N \times 4$ s. If the node hears a message in this interval, it decodes the slot number from the message and computes its own time to talk based on this slot number. So, for example if $N = 4$ and n hears a message from the node whose allocated slot number is 3, node n knows that its time to communicate is 4 seconds later. This method allows nodes to synchronize their internal clocks.

If node n, allocated slot N, does not hear anybody during its first $N \times 4$ s, n starts transmitting messages. Eventually, one of the nodes will start communicating first and all the other nodes will synchronize to it. A possible deadlock happens if all the nodes start talking at once. This is a low-probability event. During over 100 trials, we have never encountered this situation. We can reduce this probability to a very small value if one of the nodes is allocated two time slots.

Once the nodes synchronize upon deployment, they continue to transmit during their own time slots. Every time a node hears a master packet with correct CRC, the node re-synchronizes clocks. This procedure keeps the network synchronized over time, and enables robustness to clock drifts.

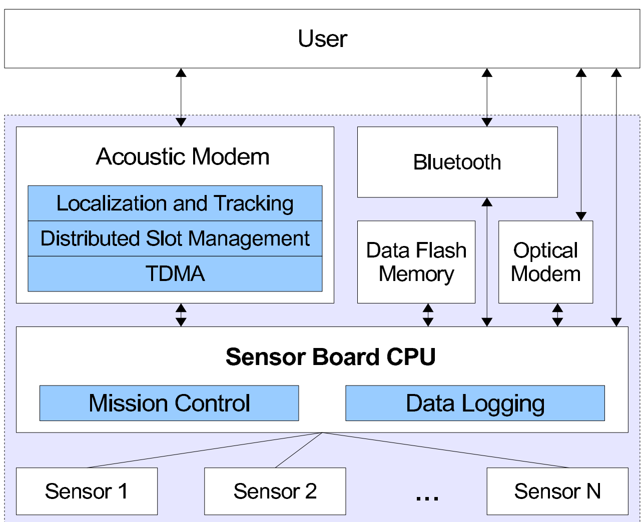

Figure 2: The architecture of the AquaNode. The arrow ended lines indicate serial links. Depending on the situation the user has several means of communicating with the node: in water using acoustic or optical communication or in air using bluetooth, optic or wired connection.

Figure 2 shows the architecture of the sensor nodes. The hardware layer includes the sensor board, the sensors, and the communication devices: the acoustic modem, the optical modem, and a bluetooth serial device (used for reprogramming when out of the water). The sensor board serves as the central controller in the system, routing messages between the devices and managing the mission control and the data. The sensor board also serves as a bridge for programming all the devices in the system. The user can also interact with the system via an external serial link. In our deployments we typically connect to the external serial link of one sensor node to have a real-time view of the network status.

4. EXPERIMENTS

We have deployed the sensor nodes and the robot in the ocean (Moorea, French Polynesia), in the river (Charles River, MA) and in a lake (Otsego, NY) and collected extensive networking and localization data for this system. We have done over 100 experiments with the sensor network.

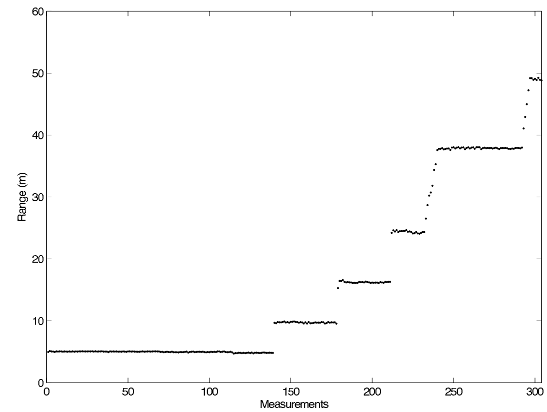

Figure 3: The ranges computed between a fixed sensor node and a moving sensor node in meters. The x-axis shows the measurement number. The y-axis shows the estimated distance. We have performed tests at 4 different distances: 4.75 m, 9.67 m, 16.15 m, and 24.7 m. The y values show the sensor network estimates.

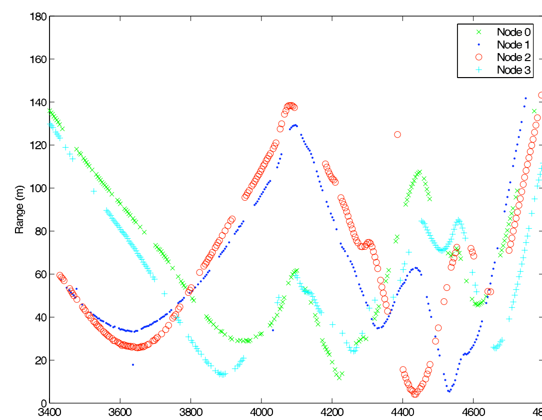

Figure 4: The ranges computed by four sensor network nodes to a moving node over time. The x-axis shows time. The y-axis shows distance in meters.

Figure 3 shows the ranges computed between a fixed sensor node anchored in a lake at a depth of 3 m to a sensor network node moved in a straight line by the underwater robot. The first set of measurements were taken at a distance of 4.75 m. The average sensor network node estimated the range at 5.01 m. The second set of measurements were taken at 9.67 m. The average estimated range was 9.72m. The third set of measurements was taken at 16.15 m. The average estimated range by the network was 16.19 m. The fourth set of measurements was taken at 24.7 m. The average estimate by the sensor network node was 24.35m.

Figure 4 shows the ranges to a moving node (the robot) computed by a sensor network of 4 nodes. In this experiment the robot was commanded to move in the field of sensor nodes. The gaps in the graph denote communications that were not successful.

5. CONCLUSION

In this paper we described the hardware and communications support for an underwater sensor network designed and implemented in our lab. Our experiments show that this is a capable and usable platform for water applications in shallow waters at depths less than 100m. We are especially interested in using this system to provide automated data collection for marine biology applications related to understanding and modeling coral reefs. This sensor network could sustain operations at greater depths by replacing the acrylic enclosure with a glass or titanium enclosure.

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