An Underwater Sensor Network with Dual Communications, Sensing, and Mobility

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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. The nodes are connected optically for higher speed point to point data transfers using an optical modem we developed. 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.**

I. INTRODUCTION

Underwater modeling, mapping, and monitoring for marine biology, environmental, and security purposes are currently done manually or using expensive hard to maneuver underwater vehicles or individual instruments. We would like to bring a new level of automation and capability to this domain in the form of versatile and easily deployable underwater sensor networks. Just like the Berkeley Mica Mote [11], the current industry standard for ground sensor networks has fueled an explosion in the development of ground and aerial sensor network applications, our goal is to develop underwater technology that will enable a similar level of automation.

More than 70% of our planet is covered by water. It is widely believed that the underwater world holds ideas and resources that will fuel much of the next generation of science and business. However, any underwater operations are fraught with difficulty due to the absence of an easy way to collect and monitor data. Underwater sensors exist but they are not networked and their use has many issues:

- Deploying, retrieving, and using the sensors is labor intensive;
- Collecting the data is subject to very long delays;
- The manual aspects of using the sensors leads to error;
- The spatial scope for data collection with individual sensor is limited;
- Individual sensors are unable to perform operations that require cooperation, such as tracking relative movement and locating events.

What is required is a low-cost, versatile, high-quality, easily deployable, self-configurable platform for underwater sensor networks that will (a) automate data collection and scale-up in time and space, (b) speed-up access to the collected data, and (c) be easy to use.

In this paper we describe the underwater sensor network hardware we designed, built, and deployed in lakes, rivers, and 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 hundreds of meters range at 300b/s). We discuss the communication performance of the network during experiments with this system in the ocean, in rivers, and in lakes. We describe the sensor network hardware, explain the communication protocols, and show results from field experiments.

The sensor nodes, which were developed in our lab, 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 and designed in our lab. The system of sensor nodes communicates with a TDMA protocol and is self-synchronizing. The system is

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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 the 2D distributed localization algorithm developed in our previous work [13].

A. 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 [2], [5], [6], [10]. 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 serial operations [11]. A cabled water operation system was described in [12]. We also build on the success of the WHOI acoustic modem [15] to develop a flexible, reprogrammable acoustic model with new capabilities such as reprogrammability, ranging, TDMA communications, and self-synchronization.

II. THE UNDERWATER SENSOR NETWORK

A. Hardware

Fig. 1. A picture of some sensor nodes drying.

In our previous work [14] we described our first underwater sensor network. This network had limited acoustic capabilities. Building on this work, we developed a second generation underwater sensor network that has retained the original goals and addressed them with a different design and enhanced capabilities.

We have built a second generation underwater sensor nodes 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 flash memory for data logging/storage. This board has temperature and pressure sensors on it, 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.

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 top side of the first generation sensor box contained a 170 mm rod with an LED beacon. The rod was used by an AUV to locate the box, dock, and pick it up. Future versions of the second generation sensor node will contain such a docking rod. In addition, the node will contain a XENON flash tube for increasing the distance for reliable node location to about 20 meters. The sensor node is powered by 7 2 amp/hour 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

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

continuously) the battery provides 2 weeks of continuous operation. In sleep mode the battery provides 1 year of continuous usage. The box is weighted to be 20% negatively buoyant, and balanced such that if dropped in water it always lands top up.

The sensor node design has been planned for operations up to 200m of depth and has been tested in a pressure chamber up to 50m. We have deployed the nodes in different ocean, lake and river environments up to 10m. The sensor node is deployed manually (by throwing overboard) or it can be deployed with high precision using a robot. The node has lines of manually adjustable length. The nodes stays suspended with weights attached to the line at the bottom of the water basin.

B. Capabilities

The sensor system was built in such a way that the system is very easy to deploy. The nodes can just be placed in the water and they will automatically localize themselves using ranges obtained from the acoustic modems. Before the nodes can localize themselves they must decide on a communication schedule. To do this we use a self-synchronizing time division multiple access (TDMA) scheme to schedule messages (see Section III).

The static localization algorithm is a robust localization algorithm we developed based on a 2D distributed localization algorithm developed in [13]. This algorithm requires the set of ranges between the sensor nodes as input.

The ranges are obtained using the acoustic modems (see Section III.) The ranges are obtained using two different methods. The first is to measure the round trip time of a message between a pair of nodes. This give us a ranges with an accuracy of ±3 cm.

The second method is to synchronize the clocks on the nodes and then use a schedule to determine when each node should send a message. The modems have temperature compensated oscillators with about one part per million drift which allows sub-meter ranging accuracy for about thirty minutes before the clocks need to be synchronized again.

In both of these cases we are only able to obtain a single range measurement at any one time. In the case where the ranging is taking place on a moving node such as the robot, this implies that between each range measurement the robot will have moved and this movement needs to be compensated for. We are currently able to obtain a single range measurement every one to four seconds.

III. COMMUNICATION

In this section we describe the acoustic protocols that give our underwater sensor network nodes the capabilities described in Section II-B.

The sensor nodes are networked dually. Optical communication allows line-of-sight fast data transfers as described in [14]. The data rate is 320 Kb/s and the nodes. Direct line of site within a 90 degree cone at 2 m (extensible to 8m using lenses) is required for optical communication.

The acoustic communication enables broadcast at lower data rates of 330 kbits/s at distances of over 400 m[2]. In this section we describe the details of the acoustic communication system.

A. Acoustic Modem Hardware

The acoustic modem is built around a Analog Device Blackfin BF533 fixed point DSP processor running at 600Mhz. For transmition the processor generate a PWM signal which is amplified by a 10W D class amplifier, operating at about 90transducer developed in house. For reception, the signal from the same transducer is passed through a band pass filter, and 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 transmition 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 5ms 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).

B. A TDMA Protocol

A typical network deployment starts with initializing the number of slots at deployment type. Typically, we start with the 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

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[2] We have only tested the system up to 400 m but we believe the range is greater and have plans to test this in the near future.

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 roundtrip 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 [7] , 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 [13].

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.

C. 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 the 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 s later. This method allows nodes to synchronize their internal clock.

If node n allocated to 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.

IV. MOBILE NODES

The underwater sensor network supports mobile nodes such as our underwater robot called the Autonomous Modular Optical Underwater Robot (AMOUR), shown in Figure 2. The robot is 15kg. with a maximum speed of 1.5m/s. It has a battery life of 8 hours.

Fig. 2. A picture of AMOUR and some sensor nodes.

The robot has all of the capabilities of the sensor boxes as well as a more advanced camera system for use in local obstacle avoidance. One of the design goals of the robot was to be inexpensive, so it does not have an expensive inertial measurement unit (IMU). Instead we rely heavily on the range measurements we obtain to the sensor nodes to determine its trajectory through the water

The job of the robot is to travel around, download data from the senor nodes optically and relocate the sensor nodes. Additionally, it gives the network dynamic sampling capabilities. If an event is happening of interest the robot can move to that area to provide denser sensor sampling. We envision having many robots in the final system to provide highly dynamic sampling and faster download of the data from the static nodes.

To be able to find the sensor nodes the robot must know precisely where it is at all times. A passive localization and tracking algorithm we developed [7] has been implemented on this sensor network system and used to localize and track the moving robot.

V. 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. Typical data from such deployments in shown in Figures 4, 3, and 5. These figures show the performance of a four node deployment.

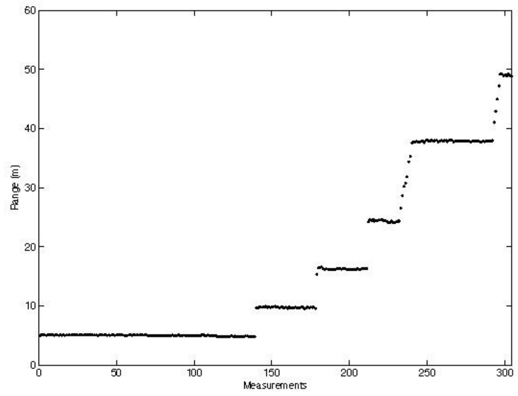

Fig. 3. The ranges computed between a fixed sensor node and a moving sensor node in meters. The x-axis shows the measurement number. The y-axis shows the estimated distance. We have performed tests at 4 different distances: 4.75 m, 9.67 m, 16.15 m, and 24.7 m. The y values show the sensor network estimates.

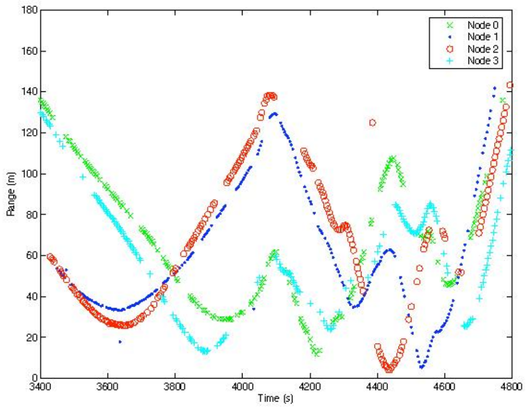

Fig. 4. The ranges computed by four sensor network nodes to a moving node over time. The x-axis shows time. The y-axis shows distance in meters.

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. Figure 5 shows the details of the communication success. For sensor network node 1, 58 % of the messages were received correctly. In the case of node 2, 64 % of the messages were received correctly. For node 3 64 % of the messages were received correctly. Finally, for node 4 the communication success rate was 50 %. The message loss was due to changing water conditions and lake bottom profile as the moving node traveled across the lake. We need to understand better how the lake geography and composition affects acoustic communication. We believe that a success rate of over 50% is sufficient for the type of monitoring and tracking applications we wish to perform with this system.

VI. 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

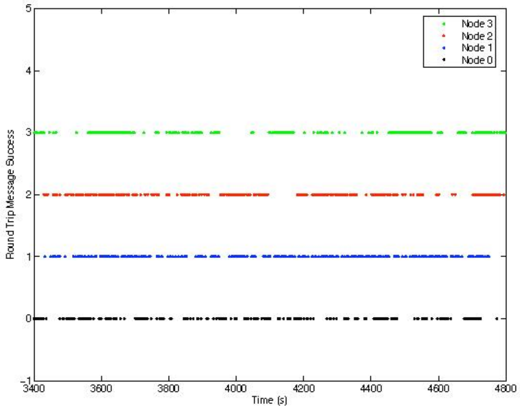

Fig. 5. Communication success for 4 sensor network nodes communicating to a moving node networked acoustically to the system. The communication for each node is displayed as a line. Gaps correspond to lost messages.

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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