Short Paper: Autonomous Depth Adjustment for Underwater Sensor Networks

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ABSTRACT

To fully understand the ocean environment requires sensing the full water column. Utilizing a depth adjustment system on an underwater sensor network provides this while also improving global sensing and communications. This paper presents a depth adjustment system for waters of up to 50m deep that connects to the AquaNode sensor network. We performed experiments characterizing the system and demonstrating its functionality. We discuss the application of this device in improving acoustic communication.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Microprocessor/microcomputer application; C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Design, Experimentation, Measurement

Keywords

Sensor Network, Ocean, Sensing, Depth Adjustment

1. INTRODUCTION

Over 70% of the earth's surface is covered in water. Sensing just the surface of these bodies of water presents a huge challenge to the scientific community. However, to better understand the dynamics and ecosystems of the ocean requires an understanding at all depths, not just the surface. What is needed is high density spatial and temporal sensing with the ability to transmit the data to scientists. This density is difficult to achieve with statically located sensors.

Instead, the sensors should move in order to cover larger regions with fewer sensors. Autonomously operated underwater vehicles (AUVs), and, in particular, underwater gliders, sense large regions of the ocean and have long deployment times. However, these systems are expensive and cannot easily hold position to obtain a time-series dataset for a particular location.

We have developed a depth adjustment system for underwater sensor networks where each node can independently control its depth in the water. The depth adjustment system enables the underwater sensor nodes to position the nodes for the purpose of deployment with a desired geometry. This positioning allows for sampling in the vertical water column, adaptively positioning nodes to optimize the acoustic communication of the system, and enabling surfacing for the purpose of node retrieval, radio communication, or locating via GPS. We are developing autonomous algorithms that perform these tasks for a network of underwater sensors. These algorithms can be used to perform one-time placement optimization of static systems or online optimization on systems with depth adjustment capabilities.

In this paper, we present the depth adjustment system and preliminary experimental results. The depth adjustment system is a module that attaches to the bottom of our core underwater sensor network nodes, called AquaNodes, described in [3, 12]. Our system allows nodes to autonomously modify their positions, which we have verified in over a dozen in-water experiments.

We start by discussing related work in Section 2. We then give an overview of the AquaNode platform in Section 3. Next, we detail the design and functionality of the depth adjustment system in Section 4. Following the system description, we present the results of preliminary experiments in Section 5 that characterize the system in air and water experiments. In addition, we illustrate how the depth adjustment system can be used to optimize acoustic communication in an underwater sensor network. We conclude and present future directions of this research in Section 7.

2. RELATED WORK

As far back as 1964, devices were constructed to sample water conditions at particular depths. Joeris devised a device which could take samples at particular depths by being lowered via a winch from a boat at the surface of the water [6]. Springer *et al.* use a winch from a surface platform to automatically lower and raise a hydrological sensor developed by the Center for Applied Aquatic Ecology at North Carolina State University [10]. The LEO-15 platform developed jointly by WHOI and Rutgers University has a bottom

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WUWNet'10, Sept. 30 - Oct. 1, 2010, Woods Hole, Massachusetts, USA

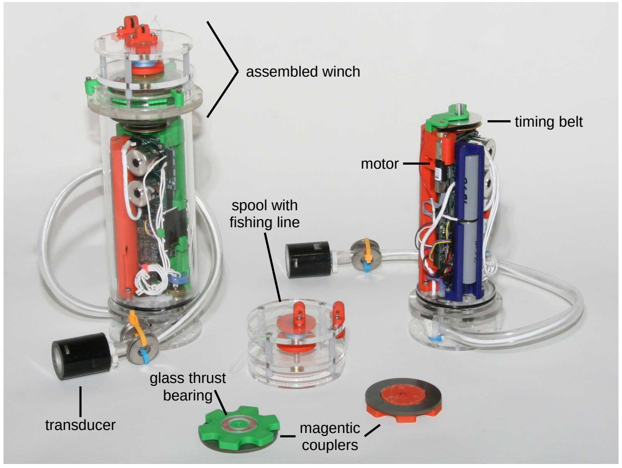

Figure 1: Depth adjustment system on AquaNode.

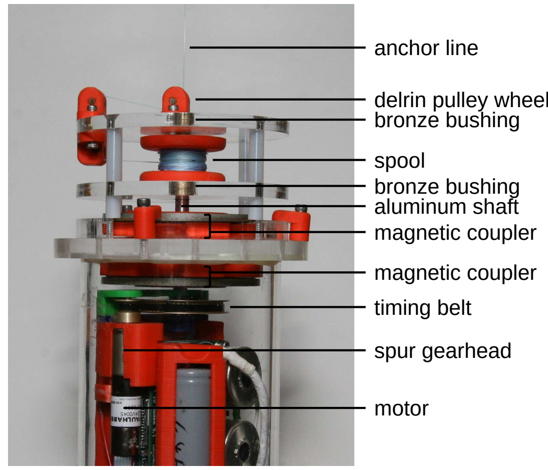

Figure 2: Depth adjustment mechanism details.

mounted winch system for water column profiling [4]. Howe and McGinnis have developed a water column profiler which travels along the mooring cable of their system and is able to recharge inductively at the surface platform [5].

Our system differs from this prior work in that we use the depth adjustment capabilities of our system for more than just water column profiling. Utilizing the depth adjustment system in conjunction with an underwater sensor network enables algorithms that improve sensing and communications. In addition, this system makes localization and recovery/deployment of large systems much easier than traditional underwater sensor networks.

A few papers discuss changing the depth of a moored underwater sensor to improve sensing or communication, however, none implement their system. Akyildiz *et al.* discuss the benefit and challenges associated with adjusting the depth of underwater sensor nodes [2]. Akkaya *et al.* propose adjusting the depths of nodes in an underwater sensor network to reduce overlap to improve sensor coverage [1]. These papers present some theory, but do not implement depth adjustment systems for underwater sensor networks.

3. AQUANODE OVERVIEW

We designed the AquaNodes to be a flexible underwater sensing and communication system. We previously described the development of the hardware, electronics, communications systems, and software for the AquaNode underwater sensor network system [3, 12]. In this paper, we add a winch-based module that allows each sensor node to dynamically adjust its depth.

Figure 1 shows a picture of the AquaNode. The AquaNode is cylindrically shaped with a diameter of 8.9cm and a length of 25.4cm without the depth adjustment mechanism and 30.5cm with it attached. It weighs 1.8kg and is 200g buoyant with the depth adjustment system attached.

Central to the AquaNode system is a 60MHz ARM7 processor. The system has pressure (for depth) and temperature sensors as well as the ability to connect other sensors. The AquaNode has an on-board 60WHr Li-Ion battery. This is sufficient for 2 days of regular acoustic communication, 2 weeks of continuous sensing, or up to a year of standby time. The desired deployment time can be achieved by varying the degrees of sensing and communication.

Communication is enabled through radio, optical, and acoustic systems. The Aerocomm AC4790 radio is used when the node surfaces via the depth adjustment system for medium-speed (57kbit), long-range (3km) communication. The acoustic and optical modems were developed in our lab. The optical modem is used for high-speed (3Mbit), short-range (3m) communication and the acoustic modem used for low-speed (300b/s), long-range (400m) communication. The acoustic modem is a frequency-shift keying (FSK) modulated modem operating with a 30KHz carrier frequency. At the core of the acoustic modem is an Analog Devices Blackfin BF533 fixed point DSP processor running at 600MHz. We measured a maximum range of about 400m and typical working range on the order of 100m.

Typically, AquaNodes are moored to an anchor and float in the water mid-column. With the addition of the depth adjustment system, the AquaNodes are able to dynamically adjust their depth.

4. DEPTH ADJUSTMENT SYSTEM

The depth adjustment system is a winch-based module that can be added to the core AquaNode system to enable depth adjustment in water of up to 50m deep. Figure 1 shows the depth adjustment system attached to an AquaNode as well as a disassembled node. The winch-based depth adjustment system is normally oriented down in the water. In the image the node is inverted for visibility.

Figure 2 depicts the details of the depth adjustment system. Internal to the node is a motor, gearhead, and timing belt drive. A magnetic coupler transmits the drive power through the AquaNode case to turn a spool of anchor line.

The depth adjustment system allows the AquaNodes to change depth in water with a speed of 2.4m/min and uses approximately 0.6W when in motion. The first component of the system is a motor that drives the winch. The motor is a 1.3W output power 1224-12V Faulhaber with a spur gearhead having a 20.6:1 reduction. The motor and gearbox assembly is 51.6mm long and 12mm wide. We connect the gearbox output to a timing belt drive that further reduces the output by 6:1, providing a total reduction of 123.6:1.

The timing belt drive connects to a custom designed magnetic coupler. The magnetic coupler transmits drive power from the inside of the housing to the outside without needing to penetrate the housing with a shaft. This has a number of advantages. First, there is no chance of leaking. Second, this allows the external components of the winch to be easily removed. Finally, the magnetic coupler is compliant to misalignments of the two sides of the coupler.

The internal and external magnetic couplers are identical and consist of four parts. We designed a holder that contains places for six magnets. We orient the magnets in the holder with poles alternating so that the magnetic field forms a closed loop when connected to the other coupler. In order to concentrate the magnetic field, a steel ring sits on top of the magnets. On the bottom of the holder we place a custom built glass thrust bearing. This gives the couplers very low-friction, ensuring efficiency.

The external magnetic coupler is submersed in salt water so resistance to corrosion is important. Both couplers use corrosion-resistant nickel plated neodymium magnets.

The external magnetic coupler attaches directly to the spool on which the anchor line is wound via an aluminum shaft. Bronze bushings support the shaft in order to allow it to spin with low-friction. Since the anchor line winds perpendicular to the shaft, three delrin pulley wheels guide and redirect the anchor line. These provide a low-friction method for properly aligning the anchor line on the spool. We use 30lb test fishing line as the anchor line on the spool. The spool holds over 50 meters of line.

5. DEPTH ADJUSTMENT EXPERIMENTS

We performed experiments to characterize the depth adjustment mechanism in air, in a pool, and in a river.

5.1 Trials In Air

We performed experiments in air to characterize the performance of the depth adjustment system. These experiments account for over 12 hours of near continuous motion of the depth adjustment system with greater than typical loads (200g) and serve as a stress test for the system.

We began by characterizing the depth adjustment system's lifting capabilities. We calculated the theoretical stall torque of the system. The motor provides 3.6mNm of torque and the spur gearhead has an efficiency of 86%. With an average spool diameter of 20mm, this results in a computed lifting force of 38.2N or a weight of approximately 3.9kg. We experimentally verified this by attaching the depth adjustment system to a spring scale. The system could support up to 3.4kg before stalling. This results in a timing belt and magnetic coupler system efficiency of 87%.

Next, we setup a compound pulley system that enables the winding of over 20m of line. We adjusted the weight on the end of the pulley to vary the load on the system. Table 1 shows the current needed from the 3-cell Li-Ion battery (nominal voltage of 12V) to move the test rig up and down. The table also lists the average speed as well as the total amount of time the winch could operate with the 60WHrs of energy available on-board the AquaNodes.

Examining the table provides insights into system operation. The speed increases and the energy decreases when moving down due to gravitational effects. The down speed stays nearly constant; however, the up speed decreases as the force increases. We expect this as the downward motion force tries to increase the motor speed, reaching a maximum. When moving upward the force acts against the motor, reducing the speed as the force increases. Additionally, even with high loads and continuous depth adjustment, the system can operate for nearly 2 days.

N	mA Down	mA Up	$\frac{m}{min}$ Down	$\frac{m}{min}$ Up	Hrs
1.5	68.36	89.12	2.90	2.75	64.63
2.5	66.70	103.29	2.88	2.66	61.69
3.0	70.16	113.85	2.97	2.72	57.60
4.0	76.80	132.48	2.91	2.62	51.42
4.4	86.07	152.76	2.82	2.50	45.41
5.4	83.30	160.01	2.82	2.36	45.64
6.9	81.78	171.95	2.84	2.31	45.11

Table 1: Current, speed, and amount of time the winch can move with different forces (in Newtons).

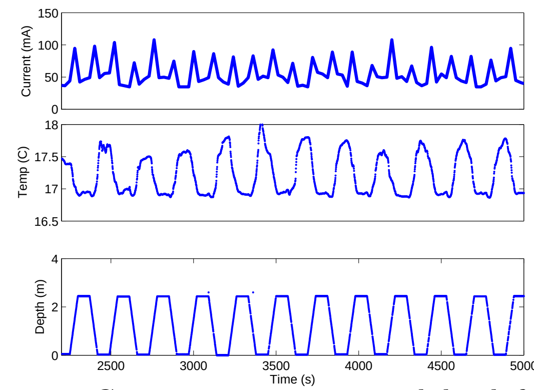

Figure 3: Current, temperature, and depth for one winch deployed in the river.

5.2 Sensing In Water

We next tested the depth adjustment system in a pool and in the Charles River in Cambridge. We performed over a half-dozen multi-hour experiments. These tests characterized the performance of the system in water and illustrated how the adjustment system captures temperature changes.

We deployed 3 AquaNodes, with depth adjustment, in the Charles River for 2 hours. Node depths ranged from 2 to 3.5m. The nodes traversed the water column every 2 minutes. Every second, the sensor nodes recorded temperature, depth, and battery current.

Figure 3 depicts 45 minutes of the results from the experiment for one node. The node used approximately 50mA when idle and about 100mA when in motion. It moved at a speed of 2.40m/min up and 2.44m/min down.

The temperature of the water varied by over 0.5°C from the surface of the water to the bottom. The response of the temperature sensor shows that it takes some time to adjust from one temperature to another indicated by the non-constant values when the node stopped moving. This is most likely caused by the heat capacitance of the temperature sensor. This indicates that at full speed the node moves too fast to accurately measure the temperature. To obtain accurate water column readings, the node must move more slowly or pause for longer periods at each depth.

6. IMPROVING COMMUNICATION

The acoustic communication channel is a challenging and fickle medium. The physical characteristics of the water and ocean floor greatly impact the success rate of acoustic

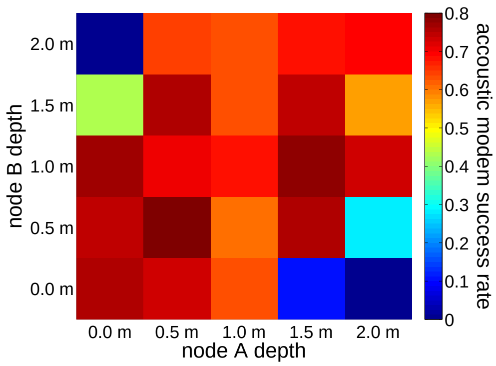

Figure 4: Acoustic communication success rate between two nodes at varying depths.

packet reception. For example, thermoclines (temperature layers found in water) can reflect acoustic signals, preventing communication between layers [9]. Adjusting the depth of the nodes in the network to optimize reception has the potential to greatly increase the network throughput.

We performed preliminary experiments to illustrate the impact of adjusting node depth on acoustic communication. We tested this in the Charles River. Due to boat traffic, we placed the nodes on the inner side of a pier, which has walls on three sides. This location is more akin to a pool than an open river. Shallow, closed-in environments challenge acoustic communication as the walls reflect the acoustic signals, causing a high level of interference [7, 8, 11, 13].

We placed 2 AquaNodes approximately 2 meters apart in water that was about 2.5m deep. The 2 nodes each moved in 0.5m steps from 0m to 2m depth. At every combination of depths each node transmitted approximately 25 packets.

Figure 4 shows the results of the packet success rate for this experiment. The success rates are asymmetric. For instance, at depths for (A,B) of (1.5,1.0) the nodes obtain better communication performance than at (1.0,1.5). On average, the acoustic modems had the greatest success rate when they were both at similar depths, whereas when the nodes were at the extremes very few packets were successful. The lack of communication is most likely caused by the non-spherical signal propagation of our cylindrical acoustic transducer. Our transducers transmit well horizontally in the water, but poor vertically. For larger inter-node ranges, this does not impact the system. However, when the nodes are closely spaced, this reduces the transmission successes for nodes at very different depths.

For more complex acoustic channels, for instance with thermoclines, we expect these discrepancies and variations to be even more pronounced. In addition, the channel quality may vary over time. As such, adjusting the depth of the nodes has the potential to greatly improve the acoustic communication in the network.

7. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a depth adjustment system for our underwater sensor network. The system can perform water column profiles, ease deployment/recovery, allow radio or GPS use at the surface, improve sensing, and improve acoustic communication. We performed a number of preliminary experiments to test and characterize the system.

The system shows great promise; however, there are several issues to address before deploying the system for long periods of time. In the future, we plan to add a tensioning system to the depth adjustment system to prevent potential winding issues arising from waves and currents. Currents can also cause the nodes to tilt in the water column. We are performing experiments to determine the maximum current the system can handle given different buoyancy and payload configurations. In addition, we plan to perform experiments to determine the maximum amount of time the system can be deployed before biofouling will impede the mechanism.

We are developing algorithmic approaches to automate the positioning of sensor network nodes in the underwater network to optimize communication throughput, sensing, and energy usage. In this paper, we presented the depth adjustment system and preliminary results showing that acoustic communication can be improved by changing the depths of the sensor nodes.

8. ACKNOWLEDGMENTS

We are grateful to DSO Singapore, MURI Antidote (138802), MURI SMARTS (N00014-09-1-1051), and NSF ITR (IIS-0426838) for supporting parts of this research.

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