Oxybuoy: Constructing a Real-Time Inexpensive Hypoxia Monitoring Platform

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Abstract. We present a low-cost sensor buoy designed for unattended dissolved oxygen measurement in aquatic environment. We describe the buoy's architectural design and three experiments that we carried out to demonstrate its viability: a laboratory test in a water tank with controlled oxygen level, a lake deployment and an extensive electric power consumption test. Our experiments indicate the viability of such an approach to dissolved oxygen monitoring and promise further advances in hypoxia studies.

Keywords: hypoxia, dissolved oxygen sensing, aquatic sensors.

1 Introduction

Hypoxia, i.e. dissolved oxygen (DO) depletion in the lower part of the water column caused by terrestrial, mostly anthropogenic, nutrient loading is an emerging national and global problem [2]. Reduced oxygen availability negatively affects biological resources, including fish [9] and commercially important invertebrate species [6]. To mitigate the environmental impact of hypoxia, the phenomenon requires extensive study. However, the dynamics of hypoxia development is poorly understood. Hypoxia tends to occur in large areas of coastal waters. For example, in the northern Gulf of Mexico, the hypoxic zone can reach $20,000\ \text{km}^2$ [12]. Traditional approaches to monitoring DO concentrations rely on using a research vessel to collect water samples for subsequent chemical analysis or to trawl DO sensors behind the vessel. These approaches necessarily limit the resolution of time-series as they are expensive due to the vessel operation costs. The measurements are weather-dependent as the ship DO sampling gear cannot be operated in rough seas. Moreover, with a single ship, it is impossible to measure DO concentration in several diverse locations simultaneously. The lack of data that can match the scale of the phenomena hinders hypoxia modeling efforts.

Remote sensing is commonly used in large-scale oceanographic studies. For example, Pearce and Pattiaratchi [7] discuss various satellite image processing techniques to determine sea-surface temperature, surface chlorophyll distribution and ocean's currents. However, satellite data require ground truthing and

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are limited to the ocean surface, whereas hypoxia develops in bottom waters. Unlike sea temperature and phytoplankton photopigments, DO does not have a proxy suitable for remote observations. Relationships between satellite-measured chlorophyll and hypoxia are confounded by the interaction of physical processes with the seasonal cycle of nutrient-enhanced productivity [12]. The limitations of traditional approaches stress the need for new high-resolution real-time monitoring tools.

An unattended buoy system becomes an attractive option. An array of such buoys deployed in coastal areas can record the DO concentration around the clock at multiple locations simultaneously and relay the data to the researcher. The technical requirements for such a buoy are as follows. A buoy needs to be capable of independent operation for up to four months – the time hypoxia occurs. It needs to be positioned 10 to 40 miles offshore and capable of sensing DO at depths of up to 50 meters. Four to six times per day sampling rate is acceptable. All these parameters are well within what present-day technology allows. However, the market for such buoys is so small that the commercial companies have to charge large premiums to recoup their development costs. Another commercial strategy is to develop a sensor platform that could be used for a variety of studies. Such platform tends to contain features that are not necessary for hypoxia study. Both approaches push the price of a commercial buoy outside the price range where extensive hypoxia studies become feasible.

Meanwhile, advances in consumer electronics and sensor technology enable such buoy construction from commercial off-the-shelf components at costs that make large hypoxia studies practical. In this paper we describe the design and testing of Oxybuoy — a proof of concept buoy for hypoxia studies. The total cost of the buoy is around $\$5,000$. Most of this cost, $\$3,500$ was due to the DO sensor itself. Communication equipment, the satellite modem and the antenna costed \$750, the rest of the electronics was a bit under \$650 and the total for casing was around \$100.

Related work. Gobat et al. [3] report on the development of an extensive military meteorological buoy systems. Guinasso et al. [4] and Bender et al. [5] describe a series of large buoy deployments for surface current measurements. Wallinga et al. [13] describe a buoy platform that can accommodate up to 100 sensors. This is a large-size buoy which requires solar batteries to power the equipment. Blain et al. [8] describe the design of a DO sensor MAREL buoy. The design was done using a membrane-based DO sensor. Such sensors are sensitive to bio-fouling and long-term measurement drift. The buoy contains a system of bio-fouling prevention that involves pumping the water from the desired depth to the surface for measurement, then automatic periodic flushing of the sensor with an anti-bacterial chlorinated solution. There is also the need for extensive sensor calibration to account for measurement drift. The data was transmitted from the MAREL buoy to shore using wireless LAN technology. Voigt et al. [11] describe their experiences building an array of temperature-measuring buoys connected by a wireless LAN.

In their position paper, Akyildiz et al. [1] describe the challenges of gathering sensor data in the marine environment. Wood et all [14] describe a design of a self-propelled float or a canoe that can follow a certain route and en route lower the sensor with a winch to a desired depth and take measurements. Another automated sensor gathering system is described by Vasilescu et al [10]. It involves robotic submarine, optical and acoustic communication, etc. These designs may be too expensive and complicated for the kind of hypoxia studies we anticipate.

The rest of the paper is organized as follows. We discuss Oxybuoy architecture in Section 2. In Section 3 we describe our experiments with the buoy deployment. In the last section we outline our future plans.

2 Oxybuoy Architecture

Design decisions. Our design decisions were dictated by the hypoxia studies requirements and the need to keep the buoy cost as low as possible. We used an optical oxygen sensor. This type of DO sensor, although relatively expensive, has fewer problems with bio-fouling and loss of calibration than the commonly used membrane-based DO sensors. There is a relatively limited amount of data to be collected during DO monitoring. Coupled with low sampling rate, it allowed us to use simple sealed batteries and avoid having to install solar panels.

Let us discuss our buoy communication decisions. Oxybuoy needs to be deployed in such distances from the shore that cellular networks are not reachable. Wireless communication at such distances requires high masts and other design options that would make the cost of the buoy prohibitively expensive. However, the hypoxia studies require data rates as low as several hundred bytes a day. Thus, we are able to use Iridium, a commercial satellite network for data transmission. The short burst data rate for one of the Iridium airtime resellers was 4 cents per byte.

Architecture description. The Oxybuoy electronics contains the following main components: Gumstix embedded board with Marvell XScale PXA270, PIC12F683 Microcontroller, 9601-D-N Satellite Modem, RS232 to SDI Converter, Marvell 88W8385 802.11(b and g) wireless card, D-OPTO optical sensor, switching relay and a switching voltage regulator. Oxybuoy architecture diagram is shown in Figure 1.

The main data processing and control over the other devices is carried out by the Gumstix embedded system. Two Gigabyte SD flash card connected to the Gumstix provides data storage for the system.

The optical sensor is controlled through SDI-12 sensor communication standard. To connect the sensor to the Gumstix we use RS232 to SDI-12 converter. The satellite modem is connected directly to one of Gumstix serial ports. The wireless card allows backup and debugging communication channel to the system. The PIC processor is used to implement the low-power operation of the system. Gumstix and PIC processors complement each other. Gumstix provides flexible user and programmer interface and ease of data storage and retrieval while PIC has low power consumption.

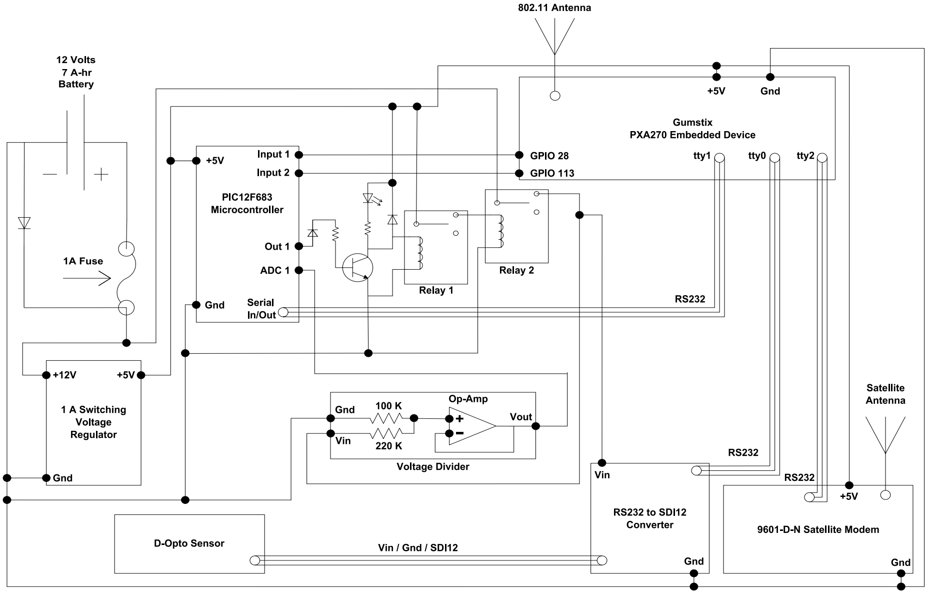


Fig. 1. Oxybuoy architecture diagram

Electric power design. There are two modes of the system operation: *active sampling mode* and power saving *sleep mode*. In the active sampling mode the system draws about 350 mA, while in the sleep mode the system draws only 11 mA. During the sleep mode only the PIC is powered up. The PIC has 1024-bit ADC connection to the battery. It is capable of reading the voltage level there. This information is helpful in determining the remaining charge left in the battery. The PIC is programmed to turn on the system to the active sampling mode. It then sends the current battery voltage level to the Gumstix processor and waits for a 2-bit signal from it to indicate the sleep period. After receiving this signal, the PIC powers down the remainder of the system.

Most of the system components require reliable 5V DC power. The DO sensor requires 8V power. We use a 5V 1A Switching voltage regulator to provide stable voltage to the system. This regulator has conversion efficiency of up to 90% which helps to minimize power consumption.

Programming and operation. Gumstix runs Open Embedded, a flavor of Linux for embedded systems. Programs and scripts are written and loaded into Open Embedded to handle communication between devices and system maintenance tasks. The system operation is as follows. When Gumstix is powered up, it receives the ADC battery power level data from the PIC processor. Then Gumstix communicates through the RS232 serial connector to the SDI-12 converter to request a reading from the DO sensor. After collecting the data, Gumstix requests the satellite modem to transmit the data to the base station. During satellite communication, the Gumstix checks the signal strength indicator. If it is too low, the data is saved on the SD card and transmitted during the next communication session. After satellite communication, the Gumstix issues the command to the PIC informing it of the sampling rate and instructing it to power down the system.

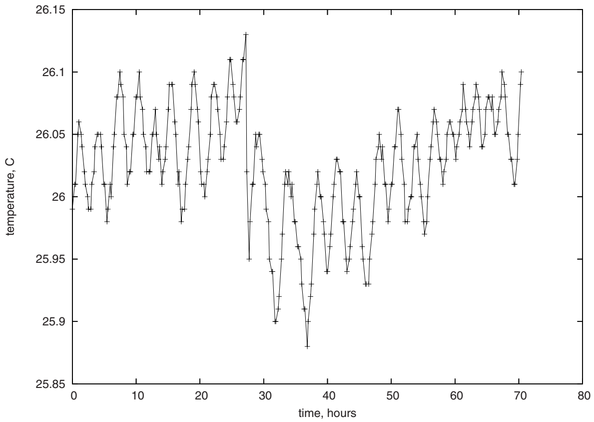
During its uptime Gumstix powers up the wireless card and remains accessible over wireless for status checks and configuration updates. Gumstix is programmed to receive control commands from the satellite. In particular the sampling rate can be changed remotely.

3 Experiments

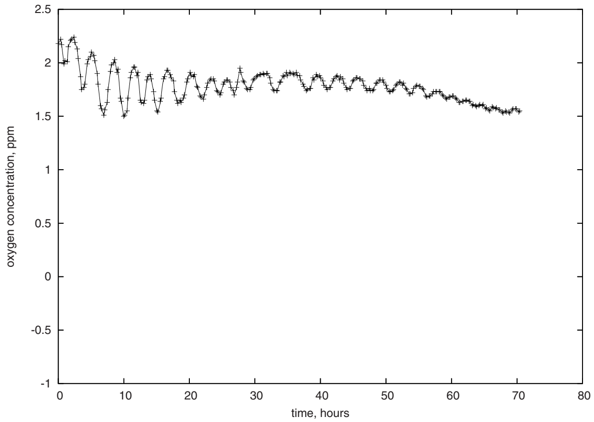
This section describes the series of experiments that we carried out to determine the viability and performance of Oxybuoy. In the first experiment we used a controlled laboratory environment to check the operation of the Oxybuoy's electronics. In the second we performed a test deployment in a small lake. In the third experiment we ran an extended power usage measurements. During the experiments, the buoy was powered by 12V DC 7Ah sealed battery.

Fig. 2. Packaging of Oxybuoy electronics for the DO lab experiment

Controlled DO lab experiment. The objective of this experiment was to test the operation of the electronics of Oxybuoy in the controlled environment. We used a water tank in a fish physiology laboratory at the University of Akron equipped for hypoxia experiments. The DO concentration in the tank was maintained at a specific level. The tank had external thermometer and YSI, Inc. DO meter. Before the experiment we calibrated our DO sensor according to the manufacturer instructions.



(a) Temperature readings.



(b) DO concentration readings.

Fig. 3. Oxybuoy measurements in the DO lab experiment

The electronic components were wall-powered. No protective packaging was used (see Figure 2). Only the DO sensor itself was submerged. We configured Oxybuoy to use the wireless card to report the measurements every 20 minutes to the wireless bridge and on to the server where the information was collected. The DO and temperature data are shown in Figure 3. The oscillation of temperature and DO concentration level are due to the design of the tank system: periodically a motor pumps fresh water into the tank. The temperature readings agree with the external meter measurements precisely while the DO concentration measurements agree with them approximately.

Bath Lake deployment. The objective of this experiment was to test the complete operation of Oxybuoy in the target environment. We deployed the buoy in Bath Lake, a small eutrophuc lake within the Bath Nature Preserve

(a) Electronics packaging of Oxybuoy.

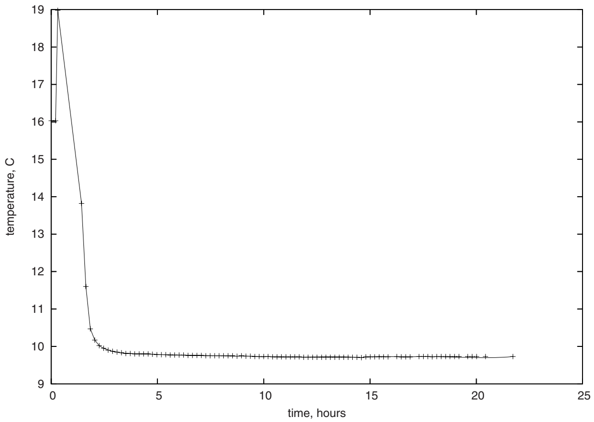
(b) Oxybuoy ready for assembly before deployment.

Fig. 4. Lake deployment experiment

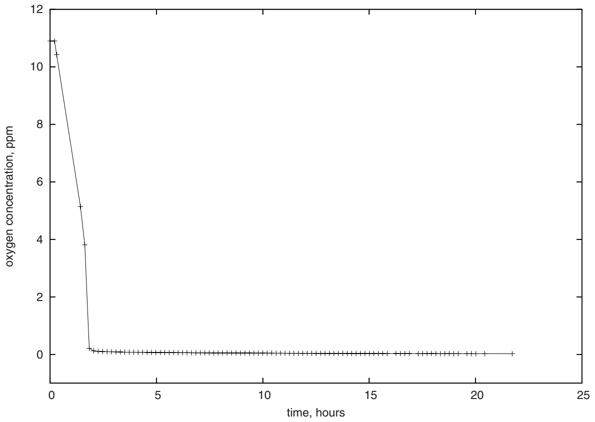
near Akron, Ohio for 7 days. To protect the electronics from water exposure we put more effort into buoy packaging. The buoy packaging in shown in Figure 4. We used 6” PVC pipe for the outer shell. For the electronics container we used a simple poster carrier pipe. The outer pipe housed the electronics, ballast and the battery. The buoy was attached by a chain to a single anchor point. The outer shell was hermetically sealed at the bottom. The oxygen sensor, and the satellite antenna cables were fed through the silicone-sealed hole in the screw-on pipe cover. This way all the possible orifices are above water. After the week-long deployment the design proved generally sound. Although, some moisture permeated the outer shell, the electronics were not damaged.

The weight of the ballast had to be carefully calculated. We wanted to ensure that the buoy is submerged deep enough in the water so that it is stable yet the the buoy cover with the instrument and antenna openings are high enough about water level to prevent continuous contact with it. We computed the weight of the ballast to have the buoy submerged about three-fourths in the water. The calculation is based on the amount water the buoy displaces, and hence the amount of buoyancy it provides.

We first tested the seal of the outer shell in a separate short deployment. Before the main deployment we tested the operation of the electronic components through first wireless connection then through the satellite messages. One of the Gumstix daughter boards was faulty and we could not use multi-mode operation in this particular experiment. We used active sampling mode only and allowed the buoy to run until the battery charge was exhausted. During the deployment, Oxybuoy reported DO measurements 6 times per hour. Running in this



(a) Temperature readings.



(b) DO concentration readings.

Fig. 5. Oxybuoy measurements in the lake deployment experiment

mode, Oxybuoy remained operational and reported DO measurements for over 18 hours. The measurements are shown in Figure 5. For testing purposes Oxybuoy started transmitting the measurements before it was deployed. Thus, the early reported data differs from the rest. The reported temperature values agree with the expectations. The DO concentration values displayed variability, which may have been due to the DO sensor lense periodically touching the sediment.

Power consumption study. To estimate the lifetime of the buoy in multimode operation we ran the electronics of the buoy in the simulated deployment. The electronics were configured to switch to data acquisition mode once an hour. The DO sensor was put in a small water container. The PIC processor recorded the battery power output and relayed it to the Gumstix processor. The Gumstix transmitted this value over the wireless network. We stopped the experiment when the battery power output fell below 8 Volts required by the DO sensor to

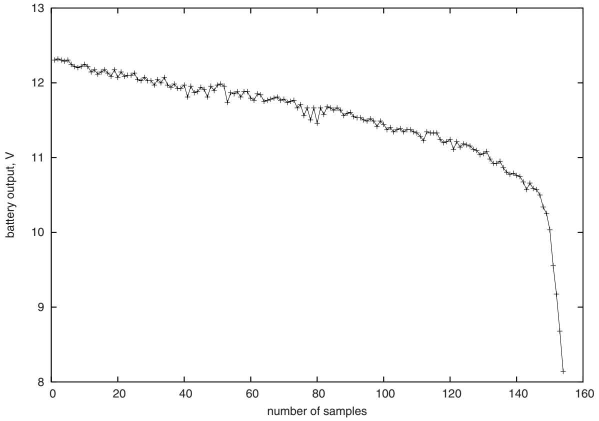


Fig. 6. Oxybuoy power consumption experiments

operate. The results are shown in Figure 6. Oxybuoy produced the total of 155 samples. At the rate of sample per hour, Oxybuoy can operate over six days.

This result agrees with the calculations. The battery is rated at 7 Ah. For this amount of time the battery is able to provide at least 10.5 V. During the active sampling mode the average current draw of Oxybuoy is 350 mA. It takes about 6 minutes to sample the DO sensor and transmit the data. This allows 120 samples. We are able to obtain more samples since we are able to use the battery until the voltage fell below 8 V. On the basis of the above data we can predict the long term-operation of the buoy. If the buoy samples every hour, its 4 month operation requires a 160 Ah battery. If only four times a day sampling is required, 28 Ah battery would be sufficient.

4 Conclusion

In this paper we described the architecture and deployment history of a prototype buoy for dissolved oxygen sensing. The experiments demonstrate the viability of this sensor platform but further studies are required. In the future we plan to evolve our sensor platform so that it is capable of unattended DO measurements for the complete duration of annual hypoxia occurrence. We plan to deploy the new buoy in both freshwater and marine environments and use it in hypoxia measurements of practical importance.

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