DOxy: Dissolved Oxygen Monitoring

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***Abstract*—Dissolved Oxygen (DO) in water is the enabler of all marine life. As low oxygen levels are the first sign of contamination and distress in bodies of water, measuring its levels are the first step in discovery and preservation efforts. Furthermore, fish farms, aquariums, and other aquaculture are in need of continued dissolved oxygen monitoring and spend a lot of money on purchasing and maintaining their sensors or on ensuring that manual readings are taken on a daily or even more often basis. Current systems and meters are either expensive, inefficient, or manual. Hence a cost-effective and sustainable automated system is necessary and long over due. DOxy, is such a system under research and development at Santa Clara University's Ethical, Pragmatic, and Intelligent Computing (EPIC) Laboratory which aims to utilize cost-effective, accessible, and sustainable Sensing Units (SUs) for measuring the dissolved oxygen levels present in bodies of water. DOxy's SUs are equipped with a High-sensitivity Pulse Oximeter meant for measuring dissolved oxygen levels in human blood and not water. Hence through a number of parallel readings with a standard dissolved oxygen meter, a conversion formula was created for DOxy which enables accurate results.**

***Index Terms*—Aquaculture, Dissolved Oxygen (DO) Monitoring, Internet of Things (IoT), Sustainable Automation, Water Quality Testing**

I. Introduction

Oxygen from the atmosphere dissolves into rivers, lakes, and oceans and is consumed by aquatic animals for breathing [1]. Dissolved oxygen (DO) is hence considered to be the most important variable of water quality as marine life will suffocate if its levels are too low. Over the past 50 years, direct measurements have shown that the amount of oxygen in global oceans has decreased by around 2 percent [2]. In order to stop deoxygenation, the data collection on the process of deoxygenation must be expanded to better understand the delicate balance of oxygenation and oxygen consumption in dynamic waters. Large-scale industrial development facilities use heavy amounts of fertilizers which easily pollute waters [1]. Overgrowth of algae, bacteria, and fungi in polluted water systems cause the oxygen to be consumed quickly and can harm aquatic life. Dissolved oxygen is a critical environmental variable because of how dynamic it is; over a matter of hours or minutes, dissolved oxygen levels can change from optimum to lethal [3]. The response time for taking corrective measures is typically short; therefore, it is critical to have a rapid and reliable method of continuously monitoring dissolved oxygen concentrations so that water facilitators can be proactive in improving the water's quality [3]. Similarly, the aquaculture industry monitors the water circulating through their system as even slight changes to the water quality can have severe effects on their crops.

II. Methodologies for Dissolved Oxygen Sensing

A. Electrochemical

1) Methodology: There are two types of electrochemical dissolved oxygen sensors: galvanic and polarographic. Both methods utilize two polarized electrodes with differences in reactivity in an inert electrolyte solution that is not part of the reaction. A semi-permeable membrane separates the electrodes and the electrolyte solution from which oxygen diffuses across. dissolved oxygen is reduced at the cathode which causes an electrical current that is carried by the ions in the electrolyte to the anode. The measured electrical current provides information on the concentration of dissolved oxygen due to their direct relation [4]. Both methods work in a similar manner except for that in the galvanic method, there is no need to allocate warm-up time due to the self-polarization of the dissimilar metals used as the anode and cathode, such as zinc and silver. However, in the polarographic method, warm-up time is essential to polarize the electrodes as the metals used, such as gold and silver, do not have a large difference in reactivity [4].

2) Problems: Although both methods have advantages, there are a number of inconveniences encountered. The electrochemical method requires maintenance every two to eight weeks and thus introduces a high maintenance cost and reduces efficiency and reliability. For the polarographic electrochemical method specifically, the electrolyte needs to be replaced, and in the galvanic electrochemical method, the anode needs to be replaced as they are used up in the internal reactions [5]. Additionally, the consumption of the substances results in the sensors having a short lifespan and thus places a high replacement frequency and cost. In addition, the measurement accuracy may be lowered due to interference by certain chemical compounds such as hydrogen sulfide found in some bodies of water that may infiltrate the membrane.

B. Optical

1) Methodology: The optical sensor consists of a semi-permeable membrane, a sensing element, a light-emitting diode, and a photodetector. The sensing element contains a luminescent dye that is immobilized in sol-gel. The dye becomes excited and emits light when exposed to the blue light emitted by the LED in the presence of DO. [4] The intensity and luminescence of the dye when exposed to blue light and the wavelength of the emitted light is dependent on the amount of dissolved oxygen in the water sample. The intensity of the returned luminescence is measured by a photodetector and is used to calculate the dissolved oxygen concentration [4].

2) Problems: Optical dissolved oxygen sensors usually require more power and take 2-4 times longer to take a measurement than the electrochemical method [4]. These sensors are also heavily dependent on temperature because of the luminescent dye's sensitivity to temperature. The luminescent dye also will eventually degrade. To maintain this type of sensor, one or two calibrations per year and a replacement cap every 18 months is needed [6]. Although the optical sensor has a lower maintenance cost, it has a greater acquisition cost which fish farmers and others small producers in the aquaculture industry may not be able to afford.

III. Existing Products

Currently, the existing dissolved oxygen meters on the market are expensive, have high maintenance costs, or do not have wireless communication integrated into the device to enable continued remote monitoring of the dissolved oxygen levels.

For instance, Cole-Parmer which is a well known scientific and industrial instrument distributor has an array of costly dissolved oxygen Meters ranging from $265 to $2459 [7] at the time of this writing. Additionally, although their products have advantages such as features that allow calibration and measurement data to be stored with a timestamp, the meters have high maintenance costs due to replacements of the chemical solutions, membranes, and caps of the measurement probes. And most importantly, the devices offered are handheld and do not provide continuous monitoring in real time.

A similar company, Hanna Instruments, offers dissolved oxygen monitors with costs ranging from $220 to $1450 [8] at the time of this writing. Their products are also high maintenance as the solutions, membranes, and probe caps needed to be replaced. Because wireless communication is not offered, testing on site is required and the device can not provide continuous monitoring.

Such devices that do not include long range wireless communication, hinder fish farmers from having the ability to detect variations in oxygen levels instantly and continuously. Therefore the farmers need to manually measure the dissolved oxygen levels several times per day which increases the amount of manual labour and reduces efficiency. Manual measurements are not only time consuming, they may also be inaccurate especially if the meters used are not calibrated and maintained correctly. Another advantage of an automated system would be the continues calibration and monitoring of individual sensors within the system which can also alert users to the malfunctioning of a sensor and or even diagnose the problem with the sensor(s) so that the technicians can repair or replace the faulty sensor(s).

IV. DOxy

DOxy is an Internet of Things (IoT) device under research and development at Santa Clara University's Ethical, Pragmatic, and Intelligent Computing (EPIC) laboratory that monitors dissolved oxygen levels in water to address the problem of poor water quality causing harm to aquatic life. Through extensive research and communicating with potential users such as fish hatcheries that rely on similar devices that are either subpar or expensive, DOxy is being designed to be accessible, compact, cost-effective, energy efficient, portable, and sustainable while needing very low maintenance and benefiting from integrated wireless communication for remote automated monitoring.

DOxy utilizes infrared technology to address the disadvantages faced by the optical, galvanic, and polarographic dissolved oxygen sensor methods. The utilization of an infrared sensor will enable a faster response time, a longer sensor lifetime and warranty, and lower maintenance and acquisition costs substantially.

A. Sensor

DOxy utilizes a MAX30102 High-Sensitivity Pulse Oximeter and Heart-Rate sensor, [9] intended for measuring the level of dissolved oxygen in human blood. The dissolved oxygen levels of water are generally lower than that of human blood. Hence, even though this sensor's readings would not initially be calibrated accurately, their consistency allows for the creation of a conversion formula. In order to find the correlation between blood oxygen levels and dissolved oxygen levels in water, a Milwaukee MW600 Dissolved Oxygen Meter [10] was used in parallel to the MAX30102 sensor to collect data from water samples with varying dissolved oxygen levels.

B. Result Mapping

A zero dissolved oxygen solution [11] (Zero), oxygenated water using an aquarium air pump (DO1 through DO4), Canada Dry carbonated water, distilled water, and the local tap water were used to test varying oxygen levels by the MW600 meter and MAX30102 sensor. DO1 through DO4 were measured after an aquarium air pump [12] pumped air into the water at a rate of 2.5L/min for 10, 20, 35, and 90 minutes respectively. With the results shown in Table 1, a linear conversion formula was constructed for the mapping of the MAX30102 sensor readings to the actual values measured by the MW600 meter.

After graphing the results as shown in figure 2, the conversion formula was derived as MW600 = MAX30102 * 1077 + 2769 by picking two points on the best-fit line and solving for the "slop" and "intercept" of the line .

Subsequent testing on different samples of water types and dissolved oxygen levels was able to attain accurate readings which agreed with the MW600 meter.

Trials	MW 600	MAX301501
Zero	0.3	2300
DO 1	0.6	2700
DO 2	1.2	4100
DO 3	3.3	6000
Canada Dry	4.95	6400
Distilled	5.05	7450
Local tap	5.2	8400
DO 4	7.8	9000

Fig. 1: Results from samples of water.

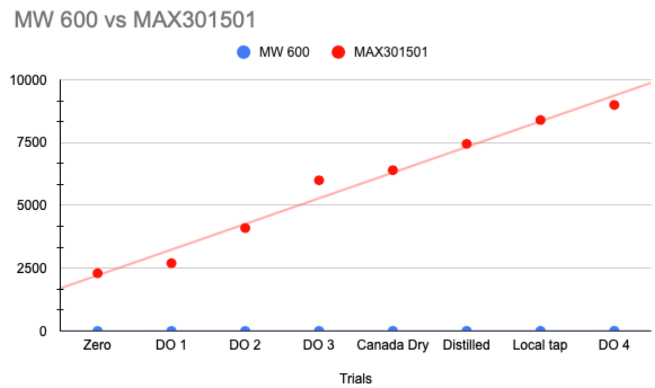
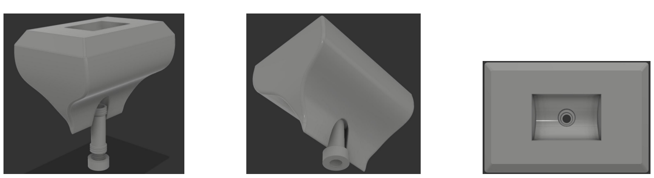


Fig. 2: Scatter graph with regression line.

V. Work In Progress

A. 3D Printed Casing

Some use cases for DOxy will include its continued operation in larger bodies of water, such as lakes and rivers. To address this requirement, a buoyant 3D printed casing as depicted in Fig 3 has been designed and is under prototyping.



(a) Open Assembly (b) Closed Assembly (c) Hardware Compartment

Fig. 3: DOxy Prototype

The casing prototype has been 3D printed with PETG filament due to its well known environmental resistance properties in aquatic and even acidic conditions [13]. Its buoyancy is achieved by having a low infill body with many sealed air pockets. To increase the prototype's hull stability as well as capsizing resistance, the bottom of the casing has been elongated, in order to move its center of mass below its center of buoyancy.

The IR sensor has been housed in a screw-on tube as shown in the open assembly diagram of the prototype in Fig 3a. The tube is removable so that it is easier to make adjustments to the sensors or to switch out hardware components. The sensor tube has threading at its bottom so that a cap can be attached, as shown in Fig 3. The tube cap has a smaller diameter opening at its bottom, as shown in Fig 3b, in order to house a glass lens which allows IR waves to pass through unhindered but does not let water to enter into the tube. Research into the best glass lens for IR transmission is still ongoing.

In the top center of the capsule, a 40 x 60mm section is hollowed out for placing all of the hardware, as shown in Fig 3c. This compartment directly connects to the sensor tube below. The bottom incline visible in the hardware compartment is needed for the main body of the SU to be easily manufactured using Fused Deposition Modeling (FDM) 3D printing, starting from the prototype's top and onward to the bottom,

The rest of the prototype's interior besides its hardware compartment is a custom infill configuration. The specific infill configuration is optimized to maximize buoyancy by encapsulating as much air as possible in isolated pockets while also ensuring a low center of mass. Keeping a low center of mass while having a low infill percentage is however, contradictory. Therefore, a variable infill rate is implemented to deposit more mass at the base of the prototype with a decreasing infill rate higher up in the body. The benefit of this is that if water enters into the hull due to a puncture for instance, it will be localized within a small pocket and not be able to permeate further into the prototype's body.

Furthermore, having a low center of mass provides stability to the prototype while it floats, making it highly resistant to capsizing. A 3D-Printed prototype of the casing has been successfully tested by being left afloat for over a week. No water entered the prototype nor did the unit capsize given several water surface turbulence testings.

A top for the prototype is in early development. The purpose of the top will be to cover the hardware compartment and also to act as a mount for both a ruggedized, water-proof solar panel which powers the system, and a small form factor communication antenna. The top will be attached to the main body of the prototype, using powerful bar magnets which are internalized within each of the parts during 3D-Printing in order to provide better water proofing than screw connectors. Extrudes from the top will overlap with the angled sides of the prototype in order to cover entry points where water could enter into the hardware compartment. Further water proofing efforts such as adding gaskets made from TPU filament and the addition of a trench around the hardware compartment that prevents any leaked water through the sides of the top from entering the hardware compartment are currently under research and development.

VI. Advantages

DOxy is a cost-effective, accessible, and sustainable dissolved oxygen monitor.

A. Cost Reduction

In contrast to the optical, galvanic, and polarographic dissolved oxygen sensor methods that are all costly both for producers to build and the users to maintain, DOxy utilizes a low-cost off the shelf blood oxygen sensor housed in a portable, compact, custom designed and 3D-printed buoyant casing that will reduce the materials and production costs immensely.

B. Accessibility

DOxy's users will be able to check the dissolved oxygen status and track the health of their aquatic life via DOxy's web application platform that processes, stores, and analyzes the data. With this feature, users will no longer have to manually check the devices in the water every hour or day. The back end of the application will utilize low cost cloud services for warehousing, managing, and analyzing the data. The front end will include both a web and platform independent mobile interface for ease of access, monitoring, and visualizing the collected dissolved oxygen level data as well as for adjusting the system's settings such as measurement rates or times.

C. Sustainability

To ensure sustainability, the following three key features are considered:

1) Sustainable Casing Material: Additive manufacturing in the form of 3D-Printing produces less waste in comparison to the traditional subtractive manufacturing methods such as molding and sculpting. The PETG filament used for 3D-Printing, is also more environmentally friendly than regular plastics. Furthermore, by using in-house techniques developed for sealing and waterproofing of 3D-printed capsules [14], DOxy's casing will be able to protect the circuitry inside from moisture without requiring toxic waterproofing chemicals used normally.

2) Sustainable Communication: In order to ensure energy saving over the communication infrastructure, DOxy will utilize ÂB as its Energy Aware Communications Protocol (EACP) [15]. ÂB is an in-house designed and developed routing protocol for agricultural and aquacultural IoT applications.

Since the ÂB communication protocol is transport layer and physical layer agnostic, DOxy will be able to use any physical layer technology available or desired such as LoRa, WiFi, Zigbee, etc. LoRa technology [16] will however be used as default due to its long 2 kilometer range wireless communications capability between the DOxy SUs across the user's desired body of water and the beach-side base station which will transmit data to DOXy's cloud infrastructure. To this end, Wisen's LoRa WhisperNodes [17] are currently being tested for use as DOxy's SU microcontroller and communications development board.

3) Sustainable Energy Sourcing: DOxy's sensing units will be battery powered. However, due to the usage of ÂB, the system will be able to take advantage of the built-in sleep cycle of the microcontroller in order to keep the SUs in a low power state except for when they are taking readings and transmitting measurements to the base station/server. Even though this will allow for long battery life, the system will utilize a solar panel in order to maintain the battery's charge and to power the system during the day even if the battery fails.

VII. Conclusion

DOxy is a low-cost, accessible, and sustainable dissolved oxygen metering system which will transform the aquaculture industry. Given the importance of monitoring dissolved oxygen levels, an IoT solution such as DOxy has the potential to reduce labor via automation, allow for early detection of changing water conditions, and increase the quality of life for marine life.

Acknowledgment

Many thanks are due to Santa Clara University's Frugal Innovation Hub and the departments of Mathematics & Computer Science, and Computer Science & Engineering for their continued support of the project.

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