Enhanced IoT Water Quality Monitoring System for Data-Based Aquaculture

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***Abstract*—Measurable water quality parameters (e.g., potential of hydrogen, electrical conductivity) are crucial factors in determining the health and viability of coastal fisheries. In particular, shellfish farms (e.g., oysters) are susceptible to changes in water quality. Farmers are often faced with the choice of relying on publicly-available data or investing in expensive commercial monitoring buoys. By gaining accurate real-time localized knowledge of process conditions, effective control methods can then be implemented to maintain optimal process conditions for improved performance and support data-driven decision making. This project focuses on the integration and testing of modern Internet-of-Things (IoT) technologies, open-source software and instrumentation, and automated data collection. The produced water quality measurement (WQM) device consists of a cost-effective PVC frame to support an Arduino-based data collection system. The data collection system monitors and collects seven water quality metrics (i.e., dissolved oxygen, electrical conductivity, oxidation reduction potential, potential of hydrogen, total dissolved solids, temperature, and turbidity). An LTE connection is used to relay the collected metrics and buoy location. The MQTT protocol is used to transmit the data, and a PC receives and translates the data into human-readable graphs and measures. An open-source user interface, developed in Python, allows the user to view time series plots of the data, see a go/no-go status regarding pre-defined process control limits, and view the location of the buoy on a map. This work focuses on the physical construction and testing of the device components and systems to support preparation for future field deployment.**

***Index Terms*—Instrumentation, Environmental, Aquaculture, IoT, Open-source, Python, MQTT**

I. Introduction

MANY physical processes present challenges in accurately predicting behavior due to the nonlinear and stochastic behavior of the process, such as electrical power systems with renewable energy sources [1]–[5], dynamic fluid systems or process system [6]–[8], and the water sector (e.g., stormwater systems) [9], [10], so data-based models (e.g., machine learning models [11]–[14]) are often needed to make predictions and support data-driven decision making [15]. Therefore, it is necessary to acquire the relevant data for such processes to adequately inspect the associated process conditions to determine the current process states to provide the needed inputs to data-based models for decision making. However, acquiring the relevant process measurements can be difficult or costly to obtain in some applications, such as aquaculture (e.g., costly sensors, harsh environments, etc.).

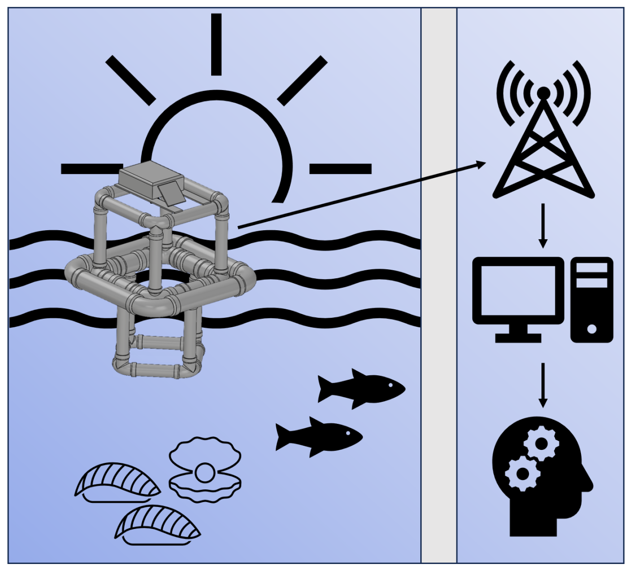

Fig. 1. Proposed cost-effective WQM system data flow via 4G network.

Ocean-based commercial water quality measurement (WQM) systems, for example, are frequently expensive and often not fully, if at all, open sourced [16], [17]. This results in either increased expenditures for farmers who wish to monitor environmental water conditions or farming practices which operate in a less data-informed manner. The Food and Agriculture Organization of the United Nations (FAO) estimates that around half of the world's seafood production is a result of aquaculture. The FAO lists digitization of aquaculture as an important innovative practice for the advancement of sustainability. Amongst the benefits of a properly-monitored aquaculture site, they include improved efficiency in farming, improved stock health, and decreased stress on the environment [18].

Oysters are one of the most commonly farmed aquatic species in the world. In the US in 2019, Oysters made up the largest volume of marine shellfish production at 42.3 million pounds and $221 million. This was more than half of the total domestic marine production by value [19]. Oysters are bivalves which feed on organic suspended particulate matter (SPM).

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Well-informed siting decisions can be more efficiently made with accurate knowledge of SPM concentrations and temporal distributions [20].

This project builds upon previous research to develop an affordable and accessible WQM platform which can be used by small coastal businesses and researchers alike [21]. The hardware used in this project consists of commercial off-the-shelf (COTS) products which are readily available for development and modification by anyone with access to online retailers and local hardware stores. The intention of this system is to augment publicly-available data with WQM data gathered by the user. The Arduino microcontroller and Python-based open-source applications allow for a cost-effective but robust and easily-modified system which can be customized for the user's needs.

The proposed key contributions of this project include the following items:

- Design for a fully open-sourced WQM buoy-based platform.
- Design for an open-sourced accompanying software, including functions for data collection, storage, communication, and a user interface to visualize the data.
- Production guideline for future builds and modifications to the proposed WQM system.
- Experimental testing to highlight performance and validate function of the proposed WQM system via laboratory and outdoor test cases.

In this work, the design and lab-testing of the WQM platform is presented as follows. Section II presents a systems overview, which consists of the electronics used (Section II-A), the software packages and design (Section II-B), and an overview of the buoy structure hardware (Section II-C). In Section III, the testing methodology is discussed. In Section IV, the results of two test cases are presented. Section IV-A presents the results of the solar PV testing, and Section IV-B details sensor performance. Finally, conclusions from this work are presented in Section V.

II. Systems Overview

Similar commercially available products can range from \$5k to \$50k, but may provide more features than are necessary in this application, as discussed in [21]. To provide a cost effective alternative, the desired cost for the proposed WQM system is $<$ \$5k. This project consists of three major subsystems: the electronics, the software, and the buoy hardware. The original buoy design is detailed in [21].

A. Electronics Overview

The hardware used in this project aims to be completely open-source and as accessible by as wide a population as possible, regardless of technical background. To this end, the Arduino platform was chosen as the basis of the electronics. As well as being widely-used for aquaculture research projects, the Arduino platform offers an abundance of compatible hardware, as well as software libraries [22]–[24].

An Arduino Mega was chosen for the micro-controller, as this controller offers sufficient processing capabilities and analog/digital inputs, while remaining cost-effective and compatible with a wide range of expansion shields. For communications testing, a Botletics SIM7000G Long-Term Evolution (LTE) shield was used. This proved to be effective for sending MQTT messages with the measured data and system status. This shield provides a 4G data connection and Global Positioning Satellite (GPS) location services. For local data storage, an Adafruit datalogging shield was selected. This shield provides a Secure Digital (SD) card interface and a real-time clock (RTC) for timekeeping purposes when 4G connections cannot be made.

The power for this system is provided by two 24 Wh LiPo batteries, which are charged by a nominal 40 watt array of solar panels. An Adafruit solar charger is used to charge one of the batteries, while the other battery is connected to and managed by the LTE shield. A buck-boost voltage regulator is used to regulate the system voltage and provide a stable 5V for the Arduino and sensors.

The WQM metrics chosen for this project include pH, Dissolved Oxygen (DO), Electrical Conductivity (EC), Total Dissolved Solids (TDS), Oxidation Reduction Potential (ORP), Turbidity, and Temperature. These metrics were chosen due to their relevance and use in the practice of oyster farming and aquaculture [25]–[29]. All sensors were chosen for their open-source availability and compatibility with the Arduino's 5V GPIO logic level. Except for the ORP sensor, which is sold by Atlas Scientific, all of the sensors chosen are branded by DFRobot. With calibration, these sensors should provide adequate accuracy for short-term deployments of this device. A complete list of electronic devices can be seen below in Table 1.

B. Software Overview

To provide an accessible and easily-modifiable software experience, the Arduino language was used for all micro-controller code [30]. A simple data collection, storage, and transmission sequence is utilized for the main Arduino program. The Arduino stores the collected data locally at every sensor reading cycle, and once five cycles of collection have been repeated, the data from all five cycles is uploaded to the MQTT server. The Arduino stays on constantly, and to conserve battery life, the LTE shield is woken only when needed. The program has been designed in such a way that minimal modification is needed by the end user, namely MQTT and LTE settings. However, due to the ease of access and availability of open-source Arduino-based sensor projects, a user with relatively little coding experience can easily integrate additional or alternative sensors. The sequence of operation for the Arduino program is shown in Fig. 2.

To facilitate use of the MQTT protocol, an Eclipse Moquitto broker was installed on Ubuntu LTS 22.10. Mosquitto is an open-source MQTT broker software that can be installed on a variety of platforms. If the user is comfortable with installing moderately complex software and changing some

TABLE I
ELECTRONIC DEVICES

Device	Description	Model #
Arduino Microcontroller	Microcontroller for interfacing with sensors and communications.	Arduino Mega 2560
LTE Shield	Communications shield for LTE and GPS connections.	Botletics SIM7000G
Datalogging Shield	SD card shield with real-time clock for local storage and time-keeping.	Adafruit Datalogging Shield
Solar Panel	5V/1.25W solar panel for keeping batteries charged.	Sunnytech GP116*116-10B250
LiPo Battery	(x2) 3.7V/6600mAh. For powering components. Dedicated battery needed for LTE shield.	Adafruit 353
Solar Charge Controller	Charge controller for regulating power from the solar panels.	Adafruit 4755
Voltage Regulator	Voltage regulator for 5V supply to Arduino and sensors.	Adafruit Powerboost 1000C
Temperature Sensor	Digital temperature probe with breakout board.	Analog Devices DS18B20 / DFRobot KIT0021
TDS Sensor	Total Dissolved Solids sensor with breakout board.	DFRobot SEN0244
ORP Sensor	Oxidation Reduction Potential sensor with breakout board.	Atlas Scientific KIT-104O
DO Sensor	Dissolved Oxygen sensor with breakout board..	DFRobot SEN0237
Turbidity Sensor	Turbidity sensor with breakout board.	DFRobot SEN0189
pH Sensor	Potential of Hydrogen sensor with breakout board.	DFRobot SEN0169-V2
EC Sensor	Electrical Conductivity sensor with breakout board.	DFRobot DFR0300-H

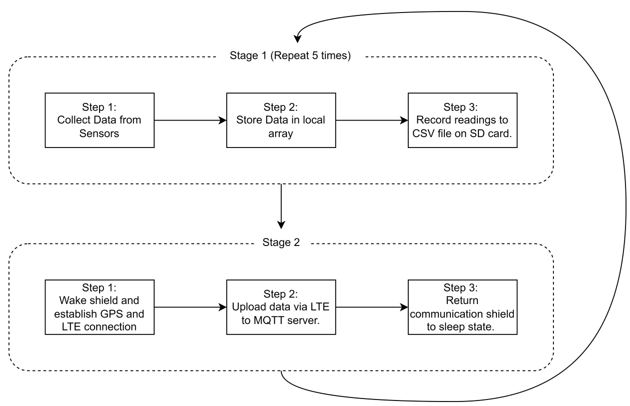

Fig. 2. Arduino program workflow.

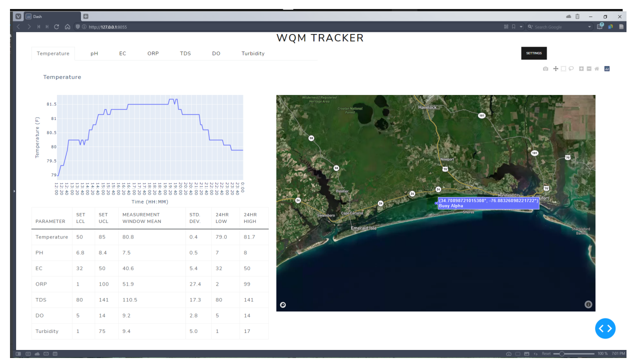

Fig. 3. Dashboard GUI with trended data and map.

simple networking setting on their router, this option may be the best. For ease of use, several paid MQTT broker services exist which were not tested during the course of this project.

For live use of the data, a data-processing and graphical user interface (GUI) program was developed in Python using Dash by Plotly. This program monitors and reads the incoming data, applies calibration factors, and displays the data to the user in tabular and graphical form. A go, no-go indication status can be applied to each metric to allow for quick assessment of water conditions. A map was implemented using OpenStreetMap. This allows the GPS data from the buoy to be read and shown in the GUI.

C. Buoy Hardware Overview

The primary material used in the construction of the buoy is polyvinyl chloride (PVC) piping. PVC piping is easily obtained from any major hardware store and lends itself to use in fabrication using only simple hand tools. The WQM design presented in this paper is based on the proposed WQM structure design presented in [21]. The WQM structure is modeled in SolidWorks. Dynamic stability analysis was used to evaluate the theoretical stability of the WQM buoy per [21].

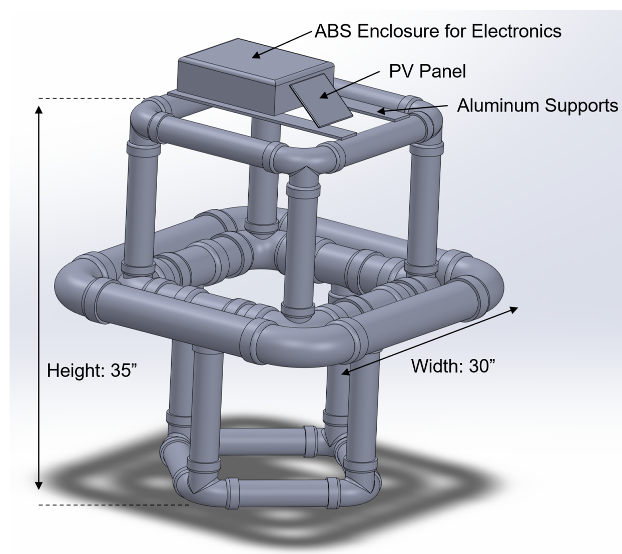

Fig. 4. Design of proposed WQM system with PVC-based buoy platform (SolidWorks).

To ensure buoyancy, the design calls for the pipes to be filled with flotation foam. This is intended to mitigate any adverse affects from a leak in the pipe joints. A pair of aluminum flat bars are used to support the housing for the electronics and solar panels. Based on the design conditions, this design keeps the electronics approximately 18 in above the surface of the water.

III. Testing Methodology

To validate the performance of the electronics and software, several laboratory and outdoor experiments were performed. Calibration of the sensors was performed using Hach HQ40D and YSI Pro 10 meters to benchmark the sensor values over the required measurement range specified in [21]. Characterization of the calibration offsets needed were recorded and used in the Python script to correct the raw gathered data (e.g., offset).

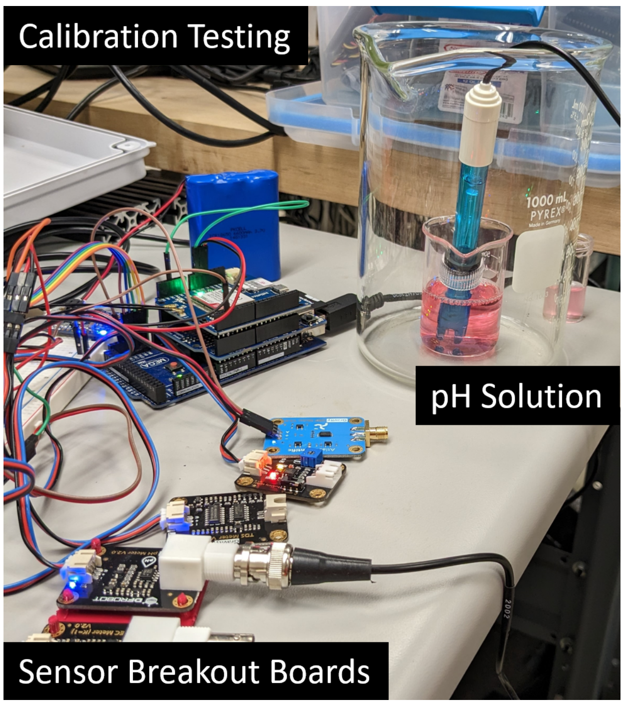

Fig. 5. Sensor desk calibration.

The communications system was tested by installing a T-Mobile LTE sim card in the system. An MQTT broker was installed on an Ubuntu LTS 22.10 server, and the user interface program was run on a laptop with a Windows 11 operating system. Stable communication was shown to be achieved using this system for a period of eight hours before the test was halted with no errors. Due to the nature of the 4G shield and signal strength at the testing location, indoor testing could not be performed. Longer outdoor tests should be performed to fully characterize the behavior of this system over time.

The power system was tested in a lab setting and found to need regulation for the PV solar power and to charge the batteries. An Adafruit PowerBoost 1000 boost-buck converter was used for this purpose. This device charges or draws power from the primary LiPo battery, depending on the strength of the PV output. An Adafruit 4755 is used to interface the PV power with the rest of the power system. The Adafruit 4755 emulates a maximum power point tracking (MPPT) controller to ensure that the power extracted from the panels is optimal. A secondary battery powers the data shield and is charged via the shield when the system is not transmitting.

An outdoor test was performed to test the sensor performance, communications operations, and battery charge when PV panels are under direct sun. The average salinity of the world's oceans is 35% [31]. An aqueous solution with the salinity of salt water was formed by mixing 30.5 grams of salt into 24 oz of filtered tap water. The sensors were placed in this solution and the setup was placed outdoors in direct sun. A similar test was run without the solar panels for the purpose of testing battery draw-down rate.

IV. Preliminary Results and Discussions

To validate performance of the proposed WQM system and highlight functional performance, considering operating conditions, two test cases are presented. Case 1, shown in Section IV-A, investigates the system performance with solar power. Then, Case 2, shown in Section IV-B, investigates the system performance with battery power only (i.e., solar power is not available).

A. Case 1: System Performance with Solar Power

The experimental configuration for the solar power test, conducted outdoors, is shown in Fig. 6. For the outdoor test, it was found that in direct sunlight, the power provided by the solar panels was sufficient to keep the batteries charged while also providing updates via 4G every at a signal frequency of one update per minute. This is an exaggerated update rate which would, in practice, be much slower, such as one update every 10 minutes to 30 minutes. The Adafruit 353 lithium ion cells used in this research have a nominal voltage rating of 3.7 V and a charging cutoff of 4.2 V. The discharge cutoff voltage is 3.0 V. Over a period of one hour with full sun, the primary battery never dropped below 4.15 V.

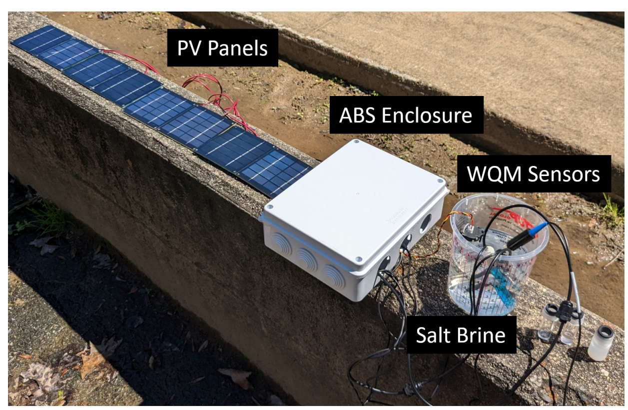

Fig. 6. Outdoor test configuration.

B. Case 2: System Performance with Battery Power

For the indoor longevity tests, the results can be seen in Fig. 7 - Fig. 12. In Fig. 7 and Fig. 8, it can be seen that the TDS and temperature values follow a similar trend pattern, which is to be expected as the salts are dissolved more thoroughly with the rise in temperature. The pH sensor appears to exhibit some settling time, with slight drift over time from about 8.0 to 8.3. This behavior will need to be explored further to determine if the drift is consistent or unique to the particular sensor chosen.

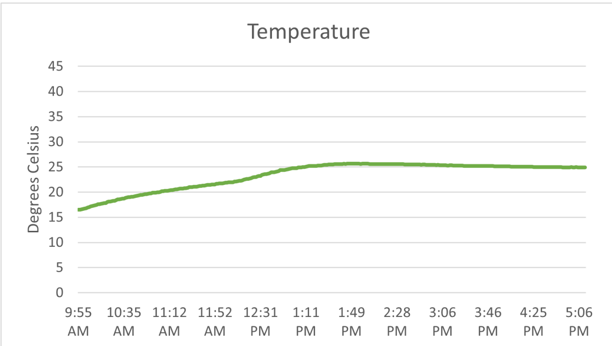

Fig. 7. Case 2: Temperature sensor performance versus time.

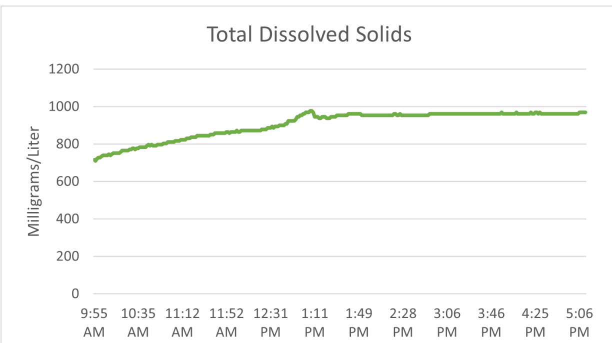

Fig. 8. Case 2: Total dissolved solids sensor performance versus time.

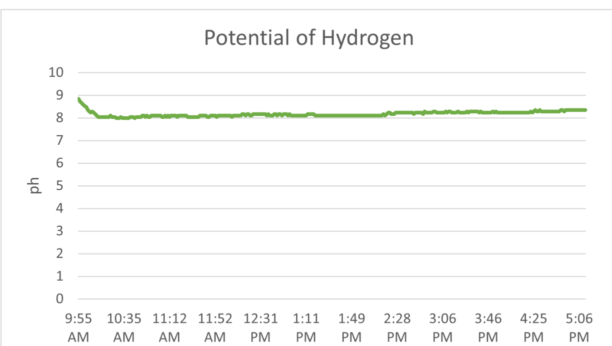

Fig. 9. Case 2: pH sensor performance versus time.

The electrical conductivity of the water was measured consistently at 16.1 mV/cm throughout the test. The ORP sensor performance is provided in Fig. 11, which shows a noisy signal, but it may be possible to add a filter in future work to reduce this noise. Over the seven-hour period of this test, the primary battery dropped from 90 to 77 percent (using a 4.2 V charge voltage as 100% and the cuttoff voltage of 3.0 V as 0%). This results in a projected battery life of two continuous days of operation without any solar recharging. This was at a polling rate of one message every five minutes. Battery life could be improved with a slower polling rate.

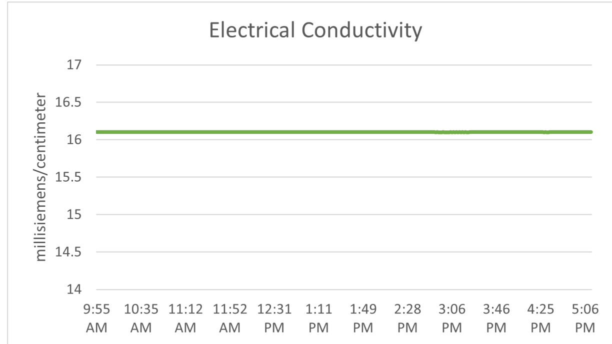

Fig. 10. Case 2: Electrical conductivity sensor performance versus time.

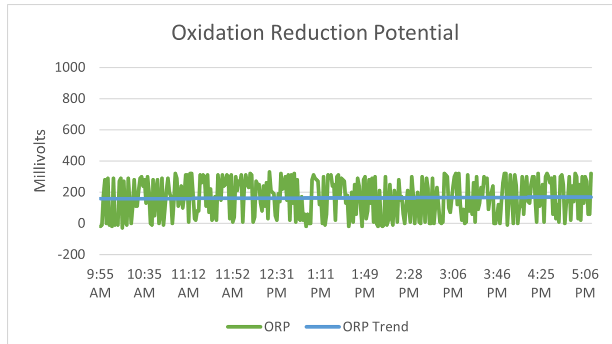

Fig. 11. Case 2: ORP sensor performance versus time.

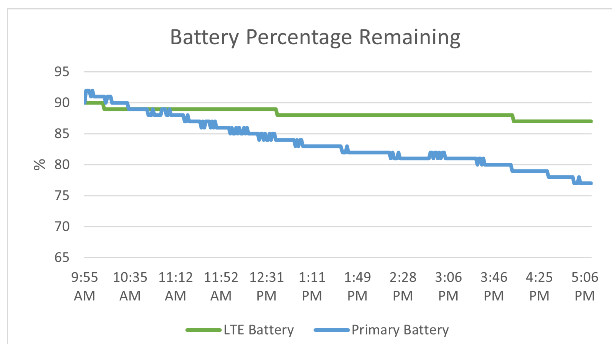

Fig. 12. Case 2: Battery power percentage versus time.

V. Conclusion and Suggestions for Future Work

Over the course of this research, a prototype model of a cost-effective WQM system was developed and tested in laboratory settings. Affordability and ease-of-access were prioritized for this model, while maintaining the needed performance for the intended application, so an Arduino Mega 2560 was used as the main controller. This choice allowed the quick development of a modular MQTT-based IOT system which can log data locally and transmit the collected data via LTE to remote systems for user interfacing and review. A GUI was developed in Python using Dash by Plotly. This user interface allows a user to quickly review the status of the buoy and view data trended over time. Data collection is timestamped and geotagged using GPS for future analysis. The power system for the sensor suite is based on LiPO batteries which are charged by solar panels. This allows the system to operate indefinitely with full days of direct sun, while also having at least 48 hours of reserve in case of poor weather conditions or unfavorable solar performance. The system developed in this work provides a solid platform for future work. A finished prototype from this work will allow smaller organizations access to data collection methods that meet their application needs.

Regarding future work, waterproofing the electronics housing and physical mounting of the hardware should be completed. This will allow for extended testing of the WQM system in the target environment (i.e., outdoor test scenarios: longer operation periods over night, battery capacity, environmental and process parameter variations, such as temperature, salinity, etc.). The DO and Turbidity sensor data are not included in the case study results for this paper, but will be included in future work to verify performance. For long-term operation, sensor drift should also be considered. Extended tests in environments that mirror the intended application process conditions will allow for characterization of sensor drift over time to support prediction and mitigation strategies.

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