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Low Cost Remote Algae Detection Utilizing Embedded Hardware, Custom Sensors, and Additive Manufacturing

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Abstract

Presented here is a low-cost embedded device and analytical application that can be utilized to automate and enhance monitoring of Harmful Algae Blooms (HABs) on Lake Erie. The system has been tested in a field deployment during the 2018 HAB season. Conventional algae sampling by boat is time consuming and is dependent on weather conditions. Current methods of automated sampling requires expensive scientific buoys that can only cover a small area. This project improves sampling efforts through a low-cost and scalable detection system that provides reliable and consistent water quality data. This system utilizes an embedded detector that collects and relays data over radio to a receiver on land. The transmitted data is stored in a database that allows the use of a smartphone application to display and analyze HAB patterns. Scientists and health officials can monitor the development of HABs in key areas and better protect water supplies. Multiple sensors provide redundancy in detecting chlorophyll concentration. The system is also capable of supporting multiple detector units, enabling economical coverage of larger areas. Additive manufacturing produces a durable, floating housing that enables operation regardless of weather conditions. The detector unit is powered by a lithium polymer battery which is recharged by a photovoltaic panel, thereby allowing continuous monitoring of HAB data.

Keywords: Embedded Systems, Algae, Sensors

1. Introduction

Harmful Algae Blooms (HABs) are a problem that continues to affect bodies of water around the world. HABs are the result of product run-on from farms that enters the watershed, fueling the growth of algae colonies. These blooms deplete oxygen in lakes, rivers and oceans, suffocating marine life and poisoning the water. This paper focuses on the Maumee Watershed and the Western Basin of Lake Erie, and the growing number of HABs faced by the area. Various entities, such as the City of Toledo and University of Toledo Lake Erie Center are tasked with monitoring the intensity of HABs and their proximity to city water intakes. This became an issue for the City of Toledo and surrounding areas in 2014 when the entire area lost access to safe drinking water due to a HAB affecting the intake located in Lake Erie. The City was not prepared due to a lack of advanced warning and a disconnection between scientists and city officials.

The process of monitoring HABs can be slow, expansive and weather dependent. For example, the YSI EXO2, a common sonde with a full sensor suite, can cost upwards of $20000[1]. These sondes are extremely accurate, however they require complex systems and buoys to be deployed for remote monitoring. Many also use radio communication frequencies that operate in licensed bands or modules that are not optimized for low power operation. These sondes are also commonly hand-operated when measurements are taken by boat in the Western Basin. These trips are weather dependent, long and require hours of work afterward to analyze samples[2]. Satellite imagery can be used to track algae blooms with a high accuracy when verified by hand. Resolution and sensing on current satellites limit their accuracy to lakes with a surface area less than 1 hectare (2.47 acres), as well as still requiring lab tests to detect cyanotoxins[3]. These methods also lack the ability to easily connect city officials and scientists without the manual compiling of reports. This can make for a dangerous situation if city officials are not fully aware of the danger a specific HAB might pose on a water intake. Manual measurements are also conducted weekly instead of tracking how HABs change over hours or a single day. This study presents a method of utilizing an embedded system that can remotely monitor water quality and provide data immediately to scientists and city officials in an easy to understand smartphone application. The entire system, needs to cost less than $150.00 to allow for a low barrier of entry for a system that is completely field tested and ready.

2. Methodology: Design

To achieve a low-cost system capable of providing simpler and round-the-clock access to HAB data requires a multi-level architecture that is expandable, dependable and configurable. This architecture relies on node-based design that has individual detectors that communicate over low-power radio to an internet-connected gateway on land. This gateway provides a web API that applications can access to interact with both data being received from the detector, as well as provide configuration changes to individual detectors on the network. At each of these levels testing was applied to verify their stability individually, in addition to overall verification that was performed to the system as a whole.

2.1 Remote Electronic Detector

To align with the goal of providing a low-cost system a custom embedded system was developed from scratch to enable the reduction of unused components and features that are commonly found on commercial microcontroller boards such as Arduino or Raspberry Pi. This lowered both the power and size requirements of the detector, thereby reducing the cost and complexity. The design of the detector followed a linear path that started with identification of sensors that would be utilized and concluded with a robust housing design.

2.1.1 sensors

When designing the sensors for the detector both accuracy and affordability were desired. To achieve this several sensors were used to corroborate and verify the readings, while also maintaining redundancy in the event of a sensor failure. Custom sensors were developed to suite the power and space constraints imposed by the embedded detector design requirements. An analysis of the cost and benefit of various sensors present in commercial water quality sondes and their relation to HABs led to the selection of four sensors that would be integrated into the detector. Before the final selection, several other sensors were considered: phosphorus, pH, and temperature. An electronic phosphorus detection method was not available, while pH did not provide enough valuable data to warrant the added cost. Temperature was cost effective, however not useful in Lake Erie as it seldom varies from the algae growth range.

2.1.2. chlorophyll sensor

Traditionally, the main sensor used for accurate detection of algae has been a phosphorus sensor as it is one of the main food sources of algae. When looking into the utilization of a phosphorus sensor it was found that there is no cost effective commercial or custom design phosphorus sensor within the price range that was set. Another flaw was that many phosphorus sensors required chemicals for their detection that would both drive up the price and would need to be replaced. Instead of using a phosphorus sensor to detect the food source of algae, a chlorophyll sensor was used to detect the ever-present chlorophyll inside algae.

The design for the chlorophyll sensor used is based on the design presented in "In Situ Measurements of Phytoplankton Fluorescence Using Low Cost Electronics[4]." This fluorometer design is attuned to the unique fluorescent properties of chlorophyll α found inside phytoplankton cells. A sample is illuminated with a blue LED (VAOL-3MSBY2) which irritates any present chlorophyll α at its maximum absorption wavelength of 440 nm. A photodiode (TSL2561) is then used in conjunction with a red filter (Roscolux Red #19) to isolate and measure the excitation spectrum. The emission LED and photodiode are placed with 45-degrees of separation relative to their focal points (Figure 1) as this was found to improve reading accuracy[4].

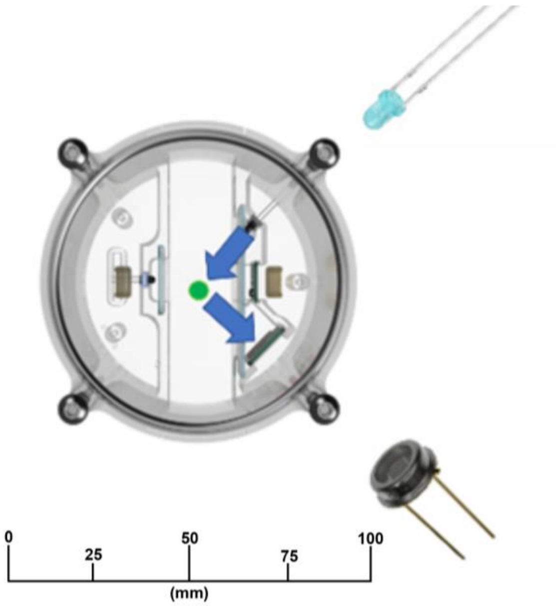

Figure 1. Integration of chlorophyll sensor into the detector. The green dot represents a water sample inside of a channel in the detector.

One large design consideration was the isolation of the chlorophyll sensor from ambient light interference[4]. To resolve this, the sensor was placed at the bottom of the sensor in a narrow channel that water flows through to minimize the amount of ambient light entering the photodiode. In additional to this, a calibration reading is taken by the photodiode before the blue LED is turned on to help identify how much ambient light is reaching it. If this calibration value exceeds a certain level, then the reading is determined to be unusable, otherwise this value is subtracted from the raw value of the photodiode reading with the blue LED activated. Another weakness of the design is it can be susceptible to false readings as a result of build-up on the window of the detector. This situation can be identified by using the detector's turbidity sensor.

2.1.3. turbidity and color sensors

A turbidity sensor was chosen to measure how thick algae in an area is by analyzing the suspended particles in the water. It was implemented by emitting a white light across a channel containing a sample of water and then measuring the diffusion with a multi-channel photodiode. Using this design, not only could turbidity be measured, but utilizing a RGBC photodiode suite allowed for an approximation of the color of the water to be constructed. The TCS34725 color sensor suite was chosen as it provides RGB and clear photodiode channels in a small package that can communicate via I^2C[5]. Although this color reading is far less quantitative than the turbidity data, it provides scientists with a visualization of how the water looks and indicates the general health of an area.

When integrating both of these sensors into the detector, the same ambient light considerations were applied to improve the overall quality of readings (Figure 2). This also includes the implementation of the same calibration step that involves turning off the LED and recording photodiode data before an actual reading is taken. The same TCS34725 color sensor used for turbidity was also used for the color reading. It was determined through laboratory experimentation that the best results occurred when the LED was placed directly across from the color sensor.

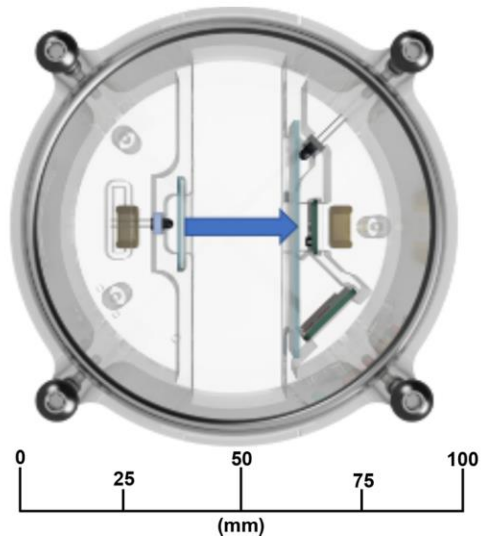

Figure 2. Light is emitted on one side of the channel, and read by the color sensor on the other. Both sensors are placed directly against clear acrylic windows to help prevent the reflection of light.

2.1.4. conductivity sensor

To add redundancy in the event of an optical sensor failure due to build up on the windows of the detector, a conductivity sensor was implemented to indicate whether a HAB is occuring. If algae are present, the conductivity sensor will have mid-range conductivity values (200 - 1000 μS/cm) compared to the low conductivity values (0 - 200 μS/cm) that Lake Erie naturally has[6]. The implementation of a conductivity sensor was simple, utilizing two wire probes separated by 3mm, protruding from the bottom of the detector. A current was then passed through the probes and the potential difference was measured by an analog to digital converter. The water conductivity is inversely proportional to the resistance between the probes.

2.1.5 calibration

Working in conjunction with The University of Toledo's Lake Erie Center, the electronic readings of the custom sensors were correlated into scientific units by developing a linear relationship in each. The Lake Erie Center's calibration standards were first verified using a YSI EXO2 sonde for measuring concentrations and purity. To calibrate the conductivity sensor a solution of about 1400 siemens per meter was used. To calibrate turbidity a solution of 100 nephelometric turbidity units (NTU) was used. For the chlorophyll sensor a solution of 73.5 micrograms per liter or 17.7 relative fluorescence units (RFU) was used for the calibration.

2.1.6 computer control

To operate the sensor package, a custom designed microcontroller board was developed. Both 32-bit and 16-bit microprocessors were analyzed for their features and compatibility with sensors. The ATmega2560 16-bit processor was selected as it provided excellent software library support, as well as light power requirements and ample program memory. A custom breakout board was developed as opposed to the utilization of a commercial one such as an Arduino Mega as is enables is significant reduction in both power profile and surface area (17.8 cm^2 verses 52.0 cm^2 on a Arduino Mega). The custom board also includes extra features such as an onboard microSD card and support for a radio module. The board was developed following all considerations and guidelines provided by the chip's manufacturer[7]. The board was milled externally and then assembled using the solder reflow practice. Due to the board's presence in natural bodies of water, all components integrated into and used in the fabrication abide by the Restriction of Hazardous Substances Directive (RoHS). The control board was tested both as a standalone device to fully integrated into the detector with the sensors to verify that the design was functioning reliably. A software verification suite was developed and utilized to test all subsystems and sensors in the detector and is executed periodically while the detector is running.

2.1.7 radio communication

To effectively monitor HABs, a detector must be able to relay its data back to a base station that can be miles away. This is further complicated by the extreme power constraints that are placed on an embedded system. Radios must also contend with licensing restrictions that vary by geographic area and obstructions. Taking these factors into consideration, the LoRa® protocol, operating on the 915.00 MHz band, was chosen for its licence free usage, price and power requirements. LoRa® is a technology developed by Semtech and includes both a physical layer, as well as a higher level LoRaWAN® layer. For this system, only the physical layer was selected as it has significantly less hardware requirements as the complete LoRaWAN® layer. The largest consideration that was made concerning the integration of the radio into the system was the impact of temperature on low-power radio[8]. To avoid the control board unnecessarily heating the radio, an elevated design was chosen, utilizing an inAir9B LoRa® module. This also allows for easier repair of the radio if a fault were to develop and isolates the radio components under an electromagnetic interference shield. The radio module can achieve long distances through line-of-sight communications, however is significantly affected by obstructions. This weakness is however mitigated due to the open areas of water that HABs develop in. Once integrated into the complete system, the radio link between the detector and a gateway/ receiver was tested at various distances to verify its capability (Figure 3). This test involved stationing the gateway outside at ground level and gradually moving the transmitter away (in increments of meters), while maintaining line-of-sight. A clear logarithmic scale emerged as separation was increased, with a R^2=0.9617. This follows the predicted signal decay of a system measured in RSSI (a logarithmic scale), showing no noticeable quality or range issues. With these results, the detector-to-detector and detector-to-ground-level-gateway range is estimated to be 1 km.

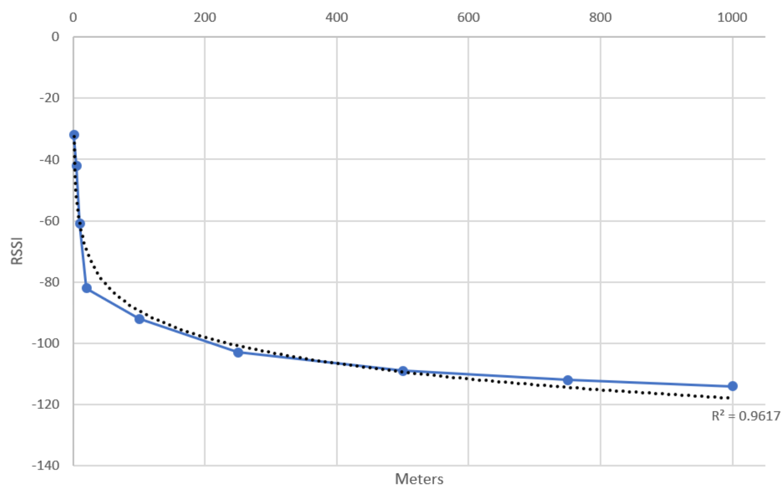

Figure 3. Received signal strength indication (RSSI) verses increasing distances.

The radio communication design also allows for basic mesh networking. This is achieved by having scheduled listen and transmit times pre-programed into each detector. When a detector receives a packet that is flagged for relay, its source and ID number are saved to prevent accidental retransmission if it were to hop multiple times. This mesh networking allows for multiple detectors to be used in series to extend the maximum range of the network. It should be noted that the range between detectors is far less than between a detector and the gateway, as the antenna of a detector is located far closer to the ground than the elevated gateway antenna.

2.1.8 solar power

Remote HAB monitoring requires a power system that can operate on a battery and recharge with a solar panel. To accomplish this, a 2,500 mAh Li-Po battery was chosen based on measured idle and peak current of the control board, radio and sensor subsystems. A safety factor of 1.5 was chosen as it provided the necessary tolerance needed for variance in the solar conditions and efficacy of the charging circuit. The daytime charge time needed to remain under 9 hours to guarantee that the system would remain charged during the shortest days of the projected season from June to October and given the worst weather conditions. To affirm the calculations, battery life trials were conducted on the completed system. This involved charging the batteries to full capacity according to the manufacturer's specifications of 4.2V at less than 0.05C5A[9]. The battery was then immediately connected into the control board's power input and the system allowed to power up. The time was recorded once the secondary status LED on the control board was lit. The system was then left to discharge undisturbed until the secondary status LED was no longer lit. This verified the exact moment that the device dropped below the minimum voltage, recording it to non-volatile memory to verify whether a reboot or brownout had occurred. The results of the battery trial showed an average lifespan of 34.46 hours, 32% above the "worse-case scenario" estimations.

2.1.9 additive manufacturing

Additive manufacturing, also known as 3D printing, was chosen for its flexibility and customizability that enabled a small and robust housing for the electronics. Alongside designing the housing, research into the effects that aqueous environments have on 3D printed housing was conducted. The first attempts in construction of the housing used traditional FDM (Fused Deposition Modeling) practices were submerged completely to a depth of 0.5 meter. These housings were printed on an Ultimaker 2+ and a Fusion3 F400. Housings that were printed with standard filament of PLA (polylactic acid) would leak within the first day no matter what percent infill was used. Other filaments, ABS (acrylonitrile butadiene styrene) and PETG (polyethylene terephthalate glycol) at 90 percent infill or greater could last up to three days without leaking. Further inspection found that leaks were caused by imperfections left behind from the layer adhesion. Post-processing was attempted to seal the imperfections in the layer adhesion. To seal the porous layers, sealants such as conformal coating and polyurethane, were applied. This added up to two additional days before the water forced its way into the housing.

To remedy the leakage through the imperfect layers a second style of 3D printing was used, SLA (stereolithography printing) also known as laser resin printing. The SLA printing was found to not be susceptible to imperfections in layer adhesion, lasting a week submerged in the same procedure that was conducted on the FMD housings. Even with the promising lab results of the SLA housing, conformal coating was added to seal up any imperfections between the housing and the acrylic windows for the optical sensors. Do to the higher price of SLA printed parts, a hybrid approach was chosen for the final design of the detector. Sections that contained electronics were printed from SLA to guarantee safety, while parts such as the foam filled floatation wings or structural solar panel brackets were printed using the cheaper FDM practice. The overall design of the detector reflects a shift from an original blocky housing that was difficult to seal, to an entirely FDM printed round housing that could be sealed with a gasket, to the final hybrid design that included flotation/ stabilization wings (Figure 4). This final design also reduced the overall volume of the detector by 30% and therefore lowered the unit cost of a detector.

Figure 4. Design evolution renderings, from original (left), testing (middle), and the final (right).

2.2 Land-Based Gateway

Once recorded data is ready to leave the detector, it is sent over radio to a gateway receiver that is stationed on land. This device is comprised of an internet connected Raspberry Pi computer that is equipped with an inAir9B radio module identical to the one inside a detector (Figure 5). The received packet is first decoded and then placed into a SQLite database using the detector's serial number and reading's timestamp. This database can then be accessed through a custom built RESTful web server implemented in the Rust programing language. This web server is also capable of receiving HTTP POST commands that can be converted into LoRa® radio packets and issued back to a network of devices.

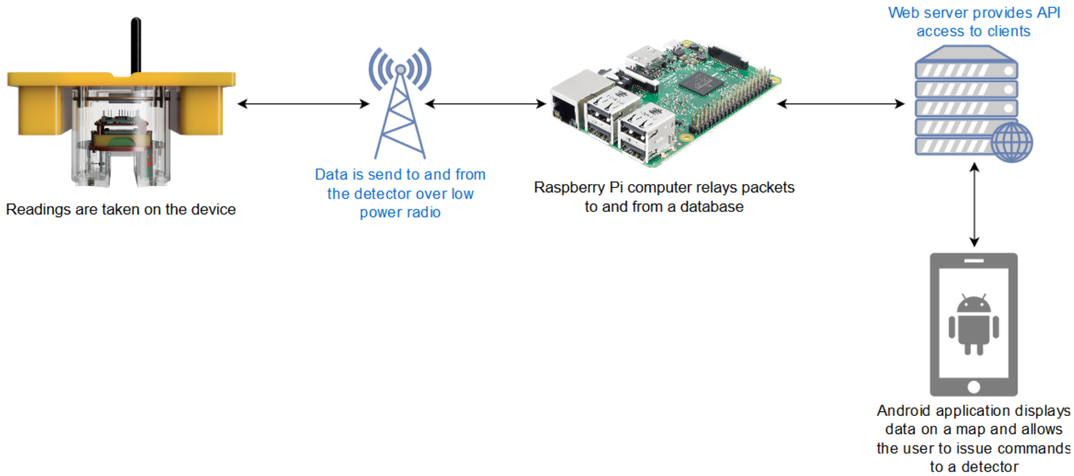

Figure 5. Architectural overview

Using basic addressing protocol, devices are able to receive individual commands to modify the configuration or state of a specific detector. The implemented operations include frequency of data recording, self-diagnostic request, enter a low-power "sleep" mode, take a reading and change radio frequency. This bidirectional data model allows for the network to be maintained and adjusted without the need to physically configure a detector.

2.3 Android Analysis App

One of the most important goals of this system is to enable scientists, public health and city officials to analyze data with ease. To assist in this, an Android smartphone application was developed to display graphs and information of readings coming from the detector (Figure 6). It also displays debug information such as firmware version, self-diagnostic data and serial number. The app retrieves its data from the gateway web server and displays it on line graphs with color representation. It is designed for simplicity and easy communication of data points. The app is also capable of issuing commands back to detectors.

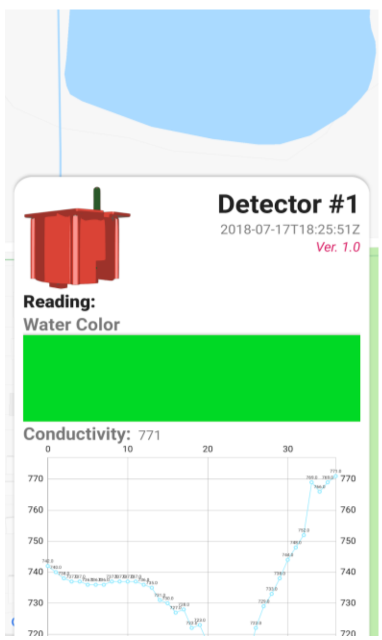

Figure 6. Android app screenshot

3. Field Testing

The final step in verifying if the system achieves the goals was to conduct a field test at the University of Toledo Lake Erie Center. The detector was deployed in an overflow pond next to Lake Erie, while the gateway module was deployed inside along the north wall of the building, shown in (Figure 7). A distance of 25 meters and a double paned glass window separated the detector and gateway. The gateway was deployed first by connecting it to a network connection and power. Prior to deployment of the detector, the battery was charged to full, record interval set to 30 minutes and device powered up. The detector was deployed on July 16th. Data being received by the gateway was then observed for three weeks. After three weeks, the detector and gateway were removed from the pond and examined.

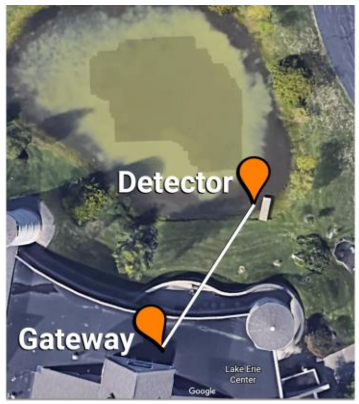

Figure 7. Overhead view of deployment locations.

4. Results

4.1 Housing Results

The housing showed signs of a slow leak that occurred around the windows in the lower section of the detector. Further analysis revealed that it was the result of the deterioration of the SLA material likely caused by the water. The areas around the windows were amongst the most exposed sections to water and are also very thin. This slow leak caused the spectral sensor to fail first, followed by the color and turbidity sensors. However, a bulkhead that separates the sensor portion from the control board and battery prevented the control board from failing. The detector was still able to maintain buoyancy despite the leak.

4.2 Sensor Results

Snippets of the readings which were taken from the detector before it became waterlogged are shown below in Figure 8. The values shown are the raw values from the detector. The spikes that appear in the conductivity and turbidity graphs are caused by sediment runoff being washed into the pond after a storm. This demonstrates that detector is capable of functioning under different weather scenarios. Some improvements could be made, for example, the chlorophyll (spectral) graph has fewer data points because some points were automatically discarded due to oversaturation of light when the sun was directly above the detector.

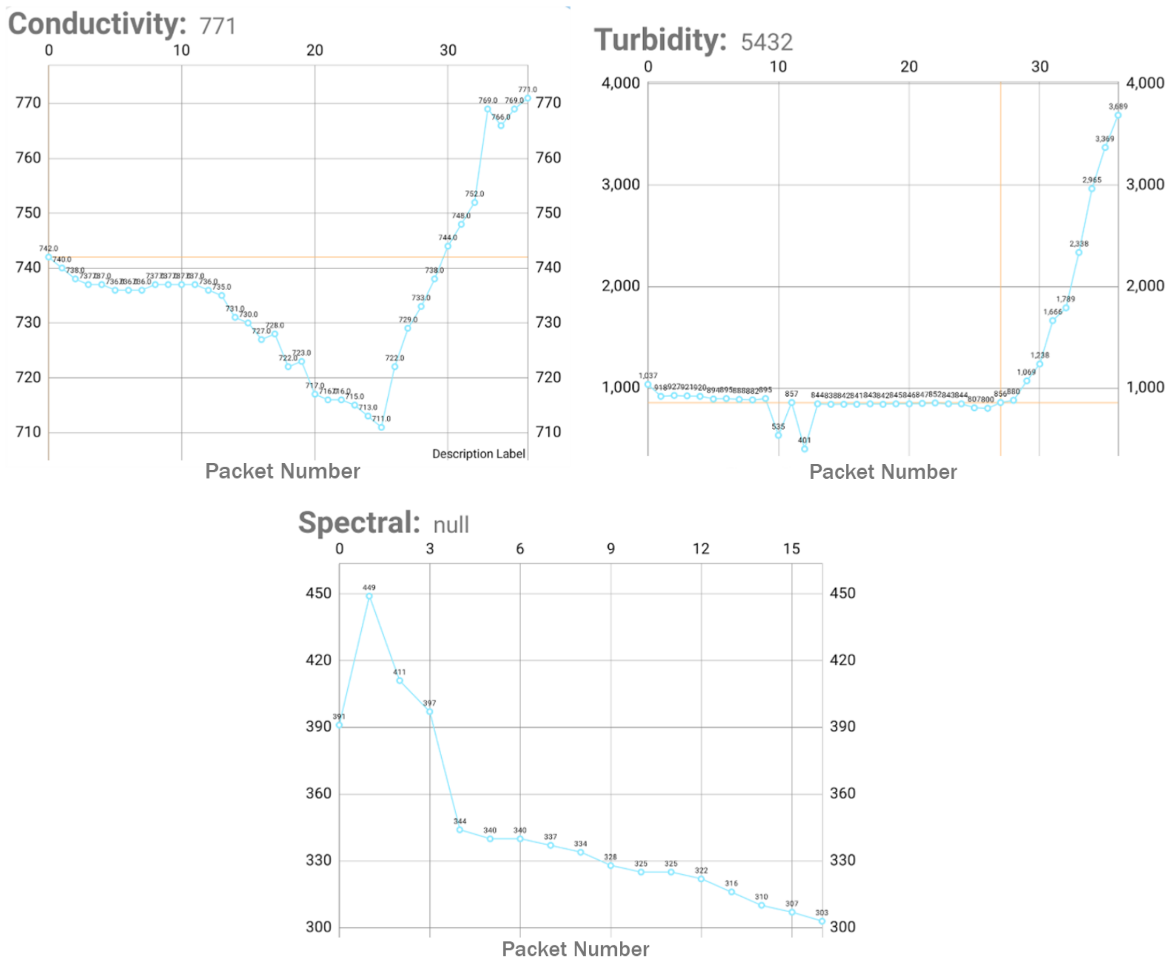

Figure 8. Sensor readings from before the detector became waterlogged. The spikes in the top two come from runoff entering the test pond after a storm.

4.3 Radio and Data Logging Results

After the completion of the field test, the system was retrieved and the contents of the microSD card were recovered from the detector. These packets were compared to the received packets on the gateway and no discrepancies were found. The system experienced no lost packets and correctly handled sensor failures, flagging sensor readings when the detector determined that a sensor had failed. The gateway also successfully stored all received data into the SQLite database and was able to retrieve it when requested by the Android app.

4.4 Cost Results

The cost goal of less than $150 for a single detector and gateway was achieved. The total price sensors was approximately $13; radio, $15; computer/power, $40; and housing, $7. The Raspberry Pi used on the gateway cost $35 and another $15 for the radio. The total cost for the system (one detector and one gateway) was $125, with $50 for the gateway and $75 per detector. Although a detector's sensor package may not provide as much data as the much more expensive commercial YSI EXO2 sonde, it does provide a first layer of analysis that can aid scientists in more detailed manual sampling trips.

5. Future Work

Future investigation could be conducted into adapting the control and radio systems to other applications. The control system was developed with adaptivity in mind and could be modified to suit a variety of environmental applications from forest fire prevention to arctic exploration. The radio system could be improved to support stronger security standards using a hardware cryptographic module and SHA256 hashing instead of the compromised SHA128 protocol. The control board could also be upgraded to support 32-bit hardware and higher accuracy analog to digital converters which improve sensor readings. Within the current algae detection system, more experimentation with the mesh-networking capabilities could be conducted to find if there is a limit on the number of detectors that can be on the network and how separation distances affect sampling.

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7. References

1. YSI Inc. "EXO2 Multiparameter Sonde." *YSI*, www.ysi.com/exo2.
2. Simosa, Alicia E. "Factors Affecting Algal Biomass Growth and Cell Wall Destruction." *ScholarWorks@Uno*, 16 Dec. 2016, scholarworks.uno.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=3357&context=td.
3. Loftin, Keith A. "Satellite Imagery Can Track Harmful Algal Blooms." *Usgs.gov*, U.S. Department of the Interior, 19 June 2017, www.usgs.gov/news/satellite-imagery-can-track-harmful-algal-blooms.
4. Leeuw, Thomas, et al. "In Situ Measurements of Phytoplankton Fluorescence Using Low Cost Electronics." *MDPI*, 19 June 2013, doi:10.3390/s130607872.
5. "TCS3472 COLOR LIGHT-TO-DIGITAL CONVERTER with IR FILTER." *Texas Advanced Optoelectric Solutions*, August 2012, https://cdn-shop.adafruit.com/datasheets/TCS34725.pdf.
6. Osswald, Joana, et al. "Toxicology and Detection Methods of the Alkaloid Neurotoxin Produced by Cyanobacteria, Anatoxin-a." *Environment International*, vol. 33, no. 8, 30 Jan. 2007, doi:10.1016/j.envint.2007.06.003.
7. "AVR® Microcontroller Hardware Design Considerations." *Microchip.com*, Microchip Technology Inc, 2017, http://ww1.microchip.com/downloads/en/AppNotes/00002519A.pdf.
8. Cattani, Marco, Carlo Alberto Boano, and Kay Römer. "An experimental evaluation of the reliability of lora long-range low-power wireless communication." Journal of Sensor and Actuator Networks 6.2 (2017): 7.
9. Hunan Sounddon New Energy Co., Ltd. "785060 2500mAh Datasheet." Jinhua Demonstration Area, Xiangtan City, Hunan Province, China, 2010.