AUTONOMOUS AQUACULTURE WATER QUALITY MONITORING SYSTEM

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Abstract

Aquaculture is one of the fastest-growing business sectors globally and is anticipated to continue to increase substantially due to the global demand for fish and shellfish. Keeping a well-maintained aquatic environment is difficult, due to the complexity of monitoring the three most common naturally occurring water contaminants: nitrite, nitrate, and ammonia. Water quality measurement is critical in all environments, including maintaining a fish tank to keep a few aquatic fish in the living room or, on a larger scale, farming fish and crustaceans for human consumption. Although every aquatic environment requires monitoring of nitrate, nitrite, and ammonia concentrations in the water, it becomes crucial for high-density aquatic farming. At night, phytoplankton and other microorganisms become inactive, resulting in an increased concentration of these three chemicals, thereby resulting in harm to the livestock. The traditional way of measuring these three elements is through test kits that rely on visual determination by paper color after chemical interaction. However, they are time-consuming, inaccurate, and messy. Having a system that checks these three levels regularly could provide a significant improvement in fish management, resulting in increased livestock size, quality, and health.

While monitoring of all chemical and environmental factors in aquaculture is important, the sole purpose of this project was to reduce the difficulty in measuring the chemicals involved in the nitrification process. The design described here documents an automated system to optically measure ammonia, nitrite, and nitrate levels in water samples in real time. The system used a color sensor and well-established chemical mixtures to determine the concentrations of each toxic nitrification by-product in an aquatic environment. The system enables the user to determine toxicity levels without the hassle of manual testing. Automation also reduces the inherent inaccuracies associated with visual inspection. With this technology, the aquaculture industry will join the Industrial Internet of Things (IIoT), becoming an automated world of measuring, filtering, and producing fish safely and more efficiently on a large-scale basis (Elsokah & Sakah, 2019).

Introduction

With an explosively growing world population, the need for efficient, economical, and safe food production is at an all-time high. Seafood sourced from international producers has traditionally involved a significant risk of chemical contamination due to a lack of quality control and chemical intervention when production problems arise abroad (Ertör, 2018; Lehane, 2013; Marine Fisheries & Aquaculture Series, 2002-2003). Additionally, the shipping and temperature controls required to transport products to the U.S. dramatically increase the carbon footprint required to create and distribute the final product (Goddek, Joyce, Kotzen & Burnell, 2019), [Egland]. Sustainable production of aquatic products within the U.S., under strict Food and Drug Authority (FDA) quality control, will result in a higher quality product, while reducing the carbon footprint required to create the product.

Seafood has slowly become considered the most efficient type of meat to produce, resulting in a push towards effective aquatic farming in recent years (Goddek et al., 2019). In any successful aquaculture environment, the water quality is of utmost importance, increasing significantly based on fish species, size, and density. Although total water quality includes chemical control as well as environmental control, the system design presented here focuses on the three direct by-products of aquatic life: ammonia, nitrite, and nitrate. While nitrogen is essential to all living organisms, as it consists of the amino acids that make up the protein needed for plant growth, the forms of nitrogen-based compounds found in the aquatic environment can be toxic if left to increase in concentration (Boyd, 2019). This toxic effect is a problem in both freshwater and saltwater environments. Two of the nitrogen-cycle by-products (ammonia and nitrite) can be controlled through bacterial processes to create the final chemical, nitrate, which can be removed using plants in a hydroponic process. In an emergency, all these chemical concentrations can be reduced through water changes.

From homeowners with fish tanks to farmers with large aquaculture farms, there is a significant problem in keeping aquatic life healthy in a cost-effective and safe way. By autonomously measuring the concentration of the chemicals produced naturally during the nitrogen cycle, a real-time monitor can reduce the manpower needed to maintain an aquaculture system, while reducing the uncertainty involved in the current visual inspection measurement process.

Conceptual Design

To understand the automation project described here, one must understand the manual process being used today to measure the chemical concentrations in aquatic environments. As an example, using a freshwater test kit to measure the ammonia concentration in a water sample, the test kit instructions entail the following steps.

1. Fill water to the 5 ml line in the provided test tube
2. Add 5 drops of solution 1
3. Add 3 drops of test solution 2
4. Shake test tube for 5 minutes
5. Let rest for 3 minutes
6. Hold test tube next to the color chart (provided) and optically determine the color level that best matches the color of the water in the test tube.

The automation process used in this current project required the design, control, and construction of an electromechanical system that could complete all steps involved in the measurement of ammonia, nitrite, and nitrate. Since chemical concentrations in water samples are independent of the size of the aquatic environment, the final design was scalable for all aquatic systems, from small personal aquariums to large-scale fish farms. Figure 1 shows the operational concept that utilizes standard freshwater test kit chemical solutions for testing the chemicals.

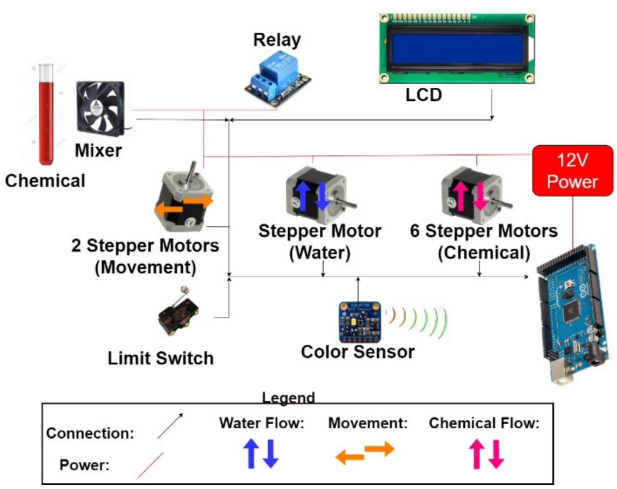

Figure 1. Conceptual block diagram.

The system initiated the measurement process by rinsing the test tube and performing a calibration using clean distilled water. From the display menu, the user could select the testing of the three chemicals individually or all consecutively. Once a test was selected, the chemical dosers precisely dispensed 5 ml of the sample water and the prescribed chemical solutions into a test vial. The stepper motors used here were calibrated to the accurate weight measure of the chemical to be dispensed, which was much more accurate than the drop-counting method required by the standard test kit. The magnetic stirrer underneath the test vial agitated the test tube mixture, allowing a uniform solution within the sample. After the chemical reaction reached equilibrium, the color sensor measured the solution's RGB values, calculated the chemical concentration based on calibration curves, and displayed the water concentration of the selected chemical. Once the test results were recorded, the test tube contents were disposed of in the waste bin and the vial was automatically rinsed and air dried in preparation for the next use.

Figure 2 shows a representation of the circuit components used in the control of the aquatic monitoring system, illustrating the mechanical, intelligence, and user interface subsections of the printed circuit board that was created for the project.

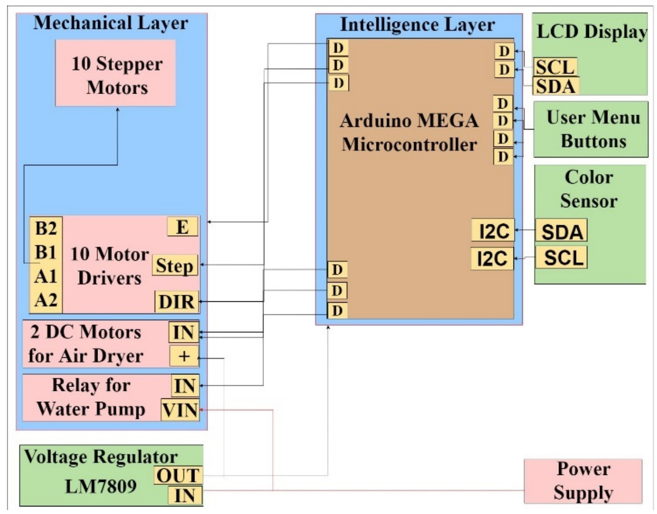

Figure 2. Functional block diagram.

The functional requirements of the monitoring system were separated into five main technical subsections: power, hardware, software, communications, and autonomous performance. Functional requirements were determined by the group using "best use scenarios" that allow for the determination of performance expectations based on a user's experience. The entire system was powered by a 12VDC power supply that was stepped down to 9V and 5V using appropriate voltage regulators. The 12V output was used to power the stepper motors, while the 9V output was used for the stepper motor control signals. The 5V output powered the DC motors, the microcontroller, and the color sensor. Although the system used numerous motors, no more than two motors were operated simultaneously. This operating concept reduced the overall current draw for the system.

The backbone of the aquatic monitoring system was an Arduino MEGA microcontroller coupled with an Adafruit TCS34725 color sensor. The purpose of using a microcontroller was to have a compact integrated circuit designed to govern all the necessary operations needed to run the autonomous system. The Arduino MEGA was the ideal microcontroller, due to the various analog, timing, and communications peripherals that can be used to operate the entire system. Equally important was the TCS34725 color sensor used to detect the color in the test tube in red, green, and blue, operating as light to digital converters to provide a digital return of red, green, and blue (RGB) color levels. To display the chemical concentrations, an LCD display was mounted on top of the system.

The functional block diagram in Figure 1 shows the flow of the power, chemicals, and water of the prototype that was built. The purpose of creating the functional block diagram was to ensure an accurate schematic for the hardware engineer to use in creating the overall aquatic monitoring System.

Functional Design

The functional block diagram in Figure 2 shows each layer, including the components associated with the mechanical, intelligence, and power layers. The aquatic monitoring system required a minimum of three different subsystems: the intelligence subsystem consisting of the Arduino MEGA, the mechanical subsystem consisting of the motors and pumps necessary to produce a flowing prototype, and the power subsystem consisting of the necessary voltage monitoring and regulation. Figure 3 shows a detailed functional block diagram for the configuration of how the color sensor was connected to the Arduino MEGA and how it was powered through the LM7805 voltage regulator.

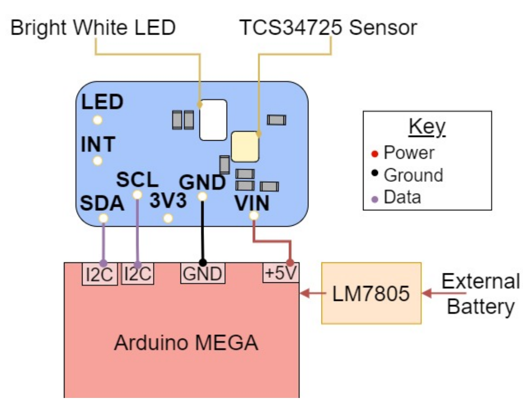

Figure 3. Sensor detailed functional block diagram.

Also in Figure 3, one can see the basic functional breakdown of the Adafruit TCS34725 color sensor. The sensor consisted of two primary components: the white LED and the sensor chip, as well as seven unique I/O ports. When the board is powered, the white LED emits a very bright light that allows the TCS34725 sensor to read color (regardless of ambient light). The four I/O pins utilized were the VIN (5V), ground, SDA (Serial Data), and SCL (Serial Clock) Pins. The Arduino MEGA provided the 5VDC signal required to power the sensor board and its associated ground as well as an I2C I/O data port that was useful for serial communication while processing and displaying the color readings from the sensor.

Figure 4 depicts the detailed functional block diagram that controlled the stepper motors. It consisted of multiple components, such as the Arduino MEGA microcontroller, DRV8825 motor driver, two voltage regulators, an external power supply of 12V, and the stepper motor itself. The stepper motors moved in discrete single steps determined by the program, allowing precise control of the motor position and speed.

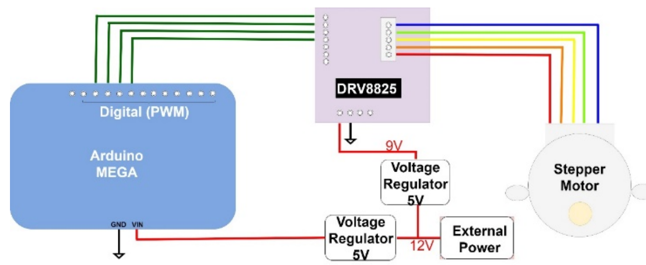

Figure 4. Stepper motors detailed functional block diagram.

Figure 5 shows a detailed functional block diagram of the DC motor, the main component for which was the Arduino MEGA microcontroller, which was used as the control mechanism to move the DC motors via a MOSFET transistor. External power was used to actuate the DC motor. The DC motors were used to provide movement of the sample throughout the process.

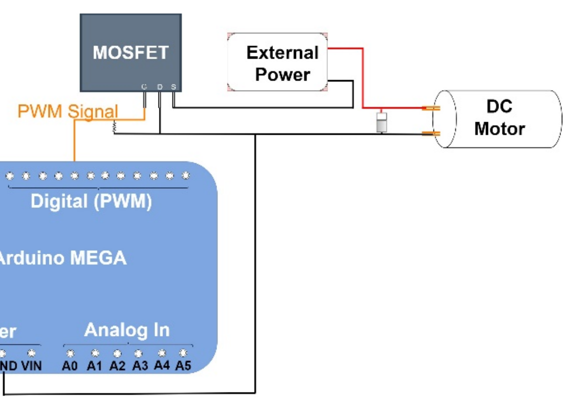

Figure 5. DC motors detailed functional block diagram.

Figure 6 is a schematic diagram showing an overview of the dosing pumps' components integrated into the aquatic monitoring system.

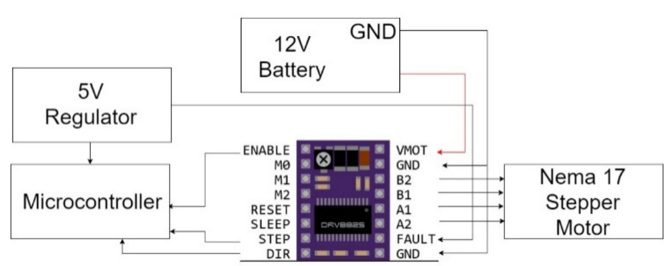

Figure 6. Dosers detailed functional block diagram.

The chemical doser was a peristaltic pump driven by a NEMA 17 stepper motor that was controlled by a DRV8825 driver board. The driver board increased the precision from full step to 132 steps, meaning that the resolution of step size was maximized 32 times and was configured using the M0-M2 pins. The stepper motor was powered by 12V through the driver board, while 5V powered the microcontroller and the driver board. The driver's inputs (power, enable, step, and direction pin) and the outputs (A1, A2, B1, and B2 stepper pins) were connected to the microcontroller and stepper motor, respectively.

Performance Specifications

The printed circuit board (PCB) design was generated using Altium, an industry standard tool for PCB layout. Design rules based on size, power consumption, and manufacturability were used in the design of the PCB. The goal was to minimize the layer count, via count, as well as board size. Figure 7 shows the final top layer of the PCB.

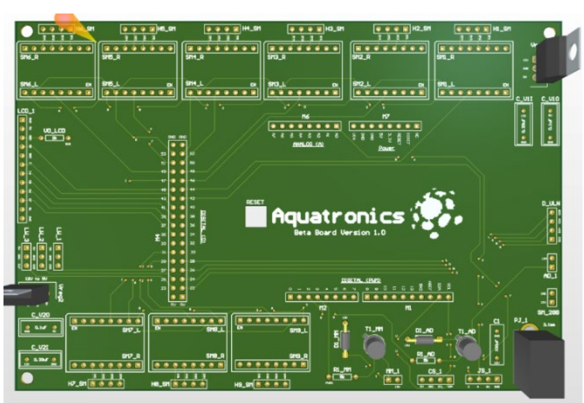

Figure 7. Top layer of the PCB.

The Aquatic Monitoring System was designed to withstand minimal water splashing and be classified as a water-resistant device. Although the final cover was not produced, Solid Works models were created that would meet the water incursion expectation. The software was expected to run without error and control the performance of the necessary functions (e.g., moving motors, reading color sensor, and processing received data) without impeding each chemical test flow. The most critical feature of the entire system was the calibration of the chemical concentration in the sample to an expected accuracy of parts per million (ppm).

Test Matrix

A test matrix was created to ensure that all hardware and software were integrated properly. Due to the size of the matrix, each of the sections was broken down into timing, automation, features, installation, and power (see Tables 1-4). Logical steps were used in determining if the test passed or failed. Only one test was chosen for inclusion here as demonstration of the testing process. All tests listed in Tables 1-4 were completed successfully. Test 2 (see Table 1) verified that the system performed all chemical tests sequentially. The following steps were performed to test full functionality.

1. Check to ensure motors are in starting position
2. Go through user interface features and click through each of the options
3. Select all three chemicals to be tested by scrolling left or right throughout the main menu and choosing "Select Chemicals" and then selecting all

	Timing						
Test Matrix	No moving parts	Response time after selection	Time it takes to dose and mix	Color sensor reads within a certain time	Moors hold enough for color sensor to read	Total time for test to finish	Total time for system to flush out and be cleaned
Test 1: Visible Inspection	X						
Test 2: Performance Test to verify feature is included		X	X	X	X	X	X
Test 3: Functional test to verify PWM	X	X	X	X	X	X	X
Test 4: Measurement & Readings				X			
Test 5: Performance test to verify Power							
Test 6: Performance test to verify continuity to µC	X	X	X	X	X	X	X
Test 7: Functional test to verify dosing accuracy			X				
Test 8: Functional test to verify dosing repeatability			X				
Test 9: Functional test to verify flush system							X
Test 10: Functional test to verify magnetic mixer			X	X			
Test 11: Functional test to verify limit switches	X	X	X		X	X	X
Test 12: Functional test to verify color sensor accuracy			X				
Test 13: Performance test to verify color sensor repeatability			X				

4. Verify that the LCD screen is easy to navigate, follows a standard layout, and is easy to use for the target market
5. Run the test by clicking the joystick and selecting "Run"
6. Verify the system responds in a timely manner
7. Validate that the chemical value displayed matched the calibration fluid to +/- 1ppm
8. Verify that all chemical waste has been disposed of properly and that all moving parts were returned to the original location
9. Check that the option to clean is listed
10. Repeat this 50 times to ensure that the system can measure and read without error and is repeatable.

Table 1. Test matrix—Timing.

Table 2. Test matrix—Automation.

Test Matrix
Test 1: Visible Inspection
Test 2: Performance Test to verify feature is included
Test 3: Functional test to verify PWM
Test 4: Measurement & Readings
Test 5: Performance test to verify Power
Test 6: Performance test to verify continuity to µC
Test 7: Functional test to verify dosing accuracy
Test 8: Functional test to verify dosing repeatability
Test 9: Functional test to verify flush system
Test 10: Functional test to verify magnetic mixer
Test 11: Functional test to verify limit switches
Test 12: Functional test to verify color sensor accuracy
Test 13: Performance test to verify color sensor repeatability

Test Matrix	Motors move to	Chemicals are dosed ba
Test 1: Visible Inspection		
Test 2: Performance Test to verify feature is included	X	X
Test 3: Functional test to verify PWM	X	X
Test 4: Measurement & Readings	X	X
Test 5: Performance test to verify Power	X	X
Test 6: Performance test to verify continuity to µC	X	X
Test 7: Functional test to verify dosing accuracy		X
Test 8: Functional test to verify dosing repeatability		X
Test 9: Functional test to verify flush system		
Test 10: Functional test to verify magnetic mixer	X	
Test 11: Functional test to verify limit switches	X	X

Test 12: Functional test to verify color sensor accuracy	
Test 13: Performance test to verify color sensor repeatability	

Table 3. Test matrix—Features.

Test Matrix	Ammonia	Nitrate	Nitrite	Clean	Display estimated finish time
Test 1: Visible Inspection	X	X	X	X	X
Test 2: Performance Test to verify feature is included	X	X	X	X	
Test 3: Functional test to verify PWM					
Test 4: Measurement & Readings	X	X	X	X	X
Test 5: Performance test to verify Power					
Test 6: Performance test to verify continuity to µC	X	X	X	X	X
Test 7: Functional test to verify dosing accuracy	X	X	X		
Test 8: Functional test to verify dosing repeatability	X	X	X		
Test 9: Functional test to verify flush system				X	
Test 10: Functional test to verify magnetic mixer	X	X	X		X
Test 11: Functional test to verify limit switches					
Test 12: Functional test to verify color sensor accuracy	X	X	X		X
Test 13: Performance test to verify color sensor repeatability	X	X	X		X

Table 4. Test matrix—Installation & Power.

Results & Future Work

The results from the autonomous system showed that it is possible to accurately dose a series of vials to read ammonia, nitrate, and nitrite RGB values. Designing a system on this engineering technology level required significant capability in mechanical, electrical, and software development as applied to motors and microcontrollers. One of the problems present in the final prototype was an unexplained variability in the baseline of the color readings that caused an extensive daily calibration to ensure correct chemical readings. The RGB values of the color sensor baseline (using clean water) were sometimes high, low, or mid-range, making it harder to pinpoint the exact concentration the autonomous system was reading. After significant analysis using Python and Excel spreadsheets, the team identified the relationship between the color data to read a concentration with a ±0.75 ppm error, well within the error margin expected from the prototype. Table 5 shows the Excel analysis of three consecutive tests of clear water and the associated RGB values versus Lux readings, which demonstrates the baseline shifts encountered.

***Table 5*. Test data.**

	RGB Data (Day 1)					RGB Data (Day 2)					RGB Data (Day 3)			
	Red	Green	Blue	LUX		Red	Green	Blue	LUX		Red	Green	Blue	LUX
0 ppm	1610	1800	1522	1202		1364	1404	1011	1039		1312	1387	1002	1029
0 ppm	1612	1793	1522	1193		1314	1366	994	1001		1349	1410	1010	1049
0 ppm	1610	1791	1529	1185		1333	1395	1021	1021		1366	1449	1045	1078

After calibration, the result of the automated chemical monitor showed a good correlation to chemical test strip measurements (visually verified) as well as sufficient repeatability of results (again, compared to repeatability of visual inspection of chemical test strips). Figures 8 and 9 show the front and top views of the final prototype, respectively.

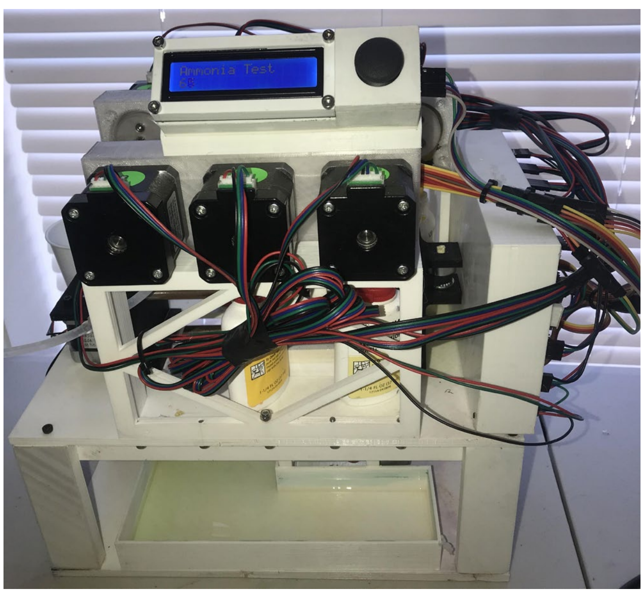

Figure 8. Final prototype front view.

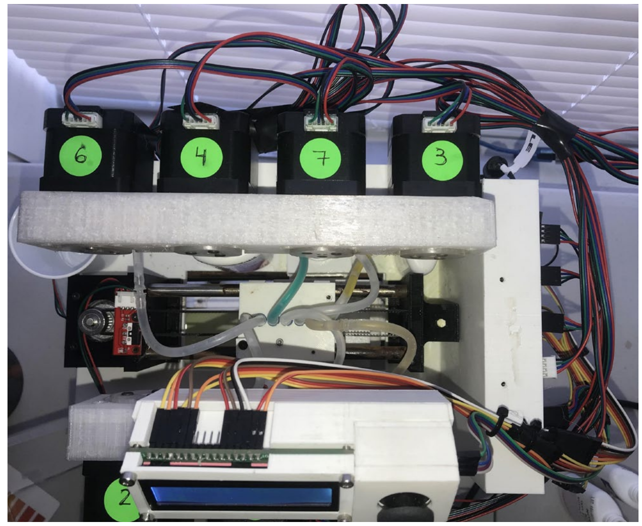

Figure 9. Final prototype top view.

To further develop the system into a commercial product, additional debugging efforts will be needed to address the stability issues in the color sensor that were temporarily fixed using software algorithms. For this project's future work, the authors plan to set up the autonomous system at a professional aquaculture facility, where it will monitor the ammonia, nitrate, and nitrite of a large freshwater prawn tank. The system is expected to report tank concentrations of each of the toxic by-products of the nitrogen cycle to better manage the tank without having to deal with paper test strips and physically observing the color samples. The chemical monitoring system described here could be implemented on any aquatic system, as the team tried to make the product as scalable as possible for both small and large fish tanks for use in the future.

Conclusions

Creating a waterproof automated system that measures ammonia, nitrite, and nitrate levels of an aquatic environment could revolutionize the chemical sensing process used throughout the aquaculture industry and save significant time and effort. The capstone team successfully finished the working prototype and acquired significant useful data to facilitate future development.

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Biographies

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GAGE ARTER is a fourth-year student in the Bachelor of Science Electronic Systems Engineering Technology program at Texas A&M University. His experience in the engineering field ranges from undergraduate research under Dr. Zoghi working with active and passive RFID and Bluetooth Low Energy and working as a lab instructor for TAMU General Engineering Department. Gage will begin working full-time in 2021 doing telecom for Oncor Electric Delivery. Gage may be reached at gagearter@tamu.edu

TRUC LE is a fourth-year student in the Bachelor of Science Electronic Systems Engineering Technology program at Texas A&M University with a minor in Cyber-Security. His related coursework includes digital electronics, circuit analysis, microcontroller architecture, and advanced local and metropolitan area networks, as he hopes to connect his love for electronics into a career choice. He is originally from Da Nang, Vietnam, and he moved to Houston, Texas, to be the first one in his family to graduate from college. He has earned a Yellow Belt in Lean Six Sigma by elevating the level of operations in improving performance by systematically reducing variation. In his free time, Truc likes to build and design simple electronic devices for entertainment used to protect children/disabled individuals from accessing high voltage outlets. Truc may be reached at tle91@tamu.edu

RAINER FINK received BS, MS, and PhD degrees in biomedical engineering from Texas A&M University (TAMU). After receiving his PhD degree, he simultaneously taught analog electronics in the Bioengineering Program and the Department of Engineering Technology at TAMU. In 1996, he joined the Electronics Engineering Technology Faculty at TAMU as an assistant professor, and he is now an associate professor. He is the Director of the Texas Instruments Mixed-Signal Test Laboratory at TAMU. He is also a Research Adjunct Professor of Electrical Engineering at the University of Arkansas, Fayetteville. His research activities include mixed-signal testing, analog circuit design, and biomedical electronics. Dr. Fink was the 1999-2000 Monague Center for Teaching Excellence Scholar. Rainer may be reached at fink@tamu.edu

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