

Ocean Acidification Tank Controller PCB Redesign

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Executive Summary

With the ever-growing amount of CO₂ released into the atmosphere, the chemical properties of the ocean's seawater are changing. More specifically, the water's pH is being lowered by absorbing CO₂. This chemical change, known as ocean acidification, can have harmful effects on the ocean ecosystem, but it is understudied as the barrier to entry into this field is very expensive. One solution presented by Dr. Kirt Onthank of Walla Walla University and in collaboration with various departments, professors, and students, created a cost-effective solution to this problem by creating an open-source tank controller for less than \$250 with the ability to control and monitor pH levels and temperatures of a controlled tank environment. Data was collected to a local SD card and an online database to be studied later.

With time, various key parts from the original tank controller have reached their end of life, making them slower, more expensive, and with limited availability when compared to other modern options. To ensure long-term reliability and revive this project, a new PCB design was required. This new design aimed to meet all the performance requirements of the original project as well as address the limitations. This required replacing the existing obsolete power supply, changing the audio jack for the temperature sensor with a BNC connector, upgrading the microcontroller for a modern unit, and designing the PCB with an emphasis on surface modules. The modules in this design were also required to be readily available, have supply longevity, and be from a reputable supplier. With these considerations in place, once the board is in the researcher's hands, it should be relatively simple to assemble.

To meet these criteria, the new PCB has the Pi Pico 2 W at the center of the design. The new PCB design also has one 120V - 5V buck converter and a 3.3V linear regulator to supply the correct power to the components. Both 5V and 3.3V were required on the PCB as 5V is used for the two-channel relay module and 3.3V is used on everything else. This new design also includes a different temperature sensor than the original as one of the goals was to replace the audio jack connector with a BNC connector. In addition to these main changes, the Ethernet module with SD card and display needed to be swapped to accommodate the new microcontroller. It's also important to mention that most of these parts are modules instead of standalone parts, as a goal of this project was to make it easy for biologists to build it without strong technical knowledge in engineering. The one exception to this goal was certain surface-mounted components, which were placed on the PCB during production.

Once the parts were selected, pin assignments for the Pi Pico 2 W were established. The schematic was then created, followed by the development of footprints for each component and the placement of each component. After determining the number of layers on the PCB, routing was completed. With the board design completed and the board and parts received, the board went through testing to verify the functionality of the components.

Codes and standards were followed according to the IPC-2221 standard, which describes minimum conductor spacing for different voltages. This project also had a \$250 budget to be cost-effective. The cost of the components of the new tank controller is \$215.88, keeping the project under budget. This project was successfully able to redesign the hardware with all components verified to be working except the Ethernet hat. This module was rendered non-functional as it was incorrectly placed onto the Pi Pico. This was a non-essential part and all other testing was completed. This improved tank controller PCB will allow the advancement of this open-source project, though additional work remains in the hardware, software, and housing. Once fully developed, this system will allow students and researchers to study the effects of ocean acidification at a fraction of the cost of traditional machinery.

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Introduction

Introduction to the Topic Area

The world is an ever-changing place, especially in recent times. One notable change is the increasing amount of CO₂ released into the atmosphere. This can have many detrimental effects on the ecosystem, especially the ocean ecosystem. When CO₂ is released into the atmosphere, the ocean water absorbs part of the CO₂, lowering its pH. This process is formally known as ocean acidification and can “1) harm life forms that rely on carbonate-based shells and skeletons, 2) harm organisms sensitive to acidity and 3) harm organisms higher up the food chain that feed on these sensitive organisms” (Environmental Protection Agency 2024). While this process can have huge effects on marine ecosystems, it is not studied as much as it should. This is because testing equipment is very expensive.

Literature Review

Loligo Systems, a company specializing in these machines, sells their professional OmniCTRL tank controller system for €9,918 EUR (~\$10,377 USD) with an additional €2,293 EUR (~\$2,403 USD) per additional tank. These devices communicate over LAN/ethernet or Bluetooth and include features such as monitoring, logging, and control over water temperature, dissolved oxygen, pH/CO₂, and salinity from multiple tanks (Loligo Systems 2024). Other commercially available recreational units are available. These tank controllers can range from the premium end of the market like the Neptune ApexEL Controller System for \$560 to a cheap \$215 controller from American Marine Inc. known as the Pinpoint pH Controller. The ApexEL Controller System allows users to monitor and control a tank’s temperature, pH, outlets, 24VDC accessories, WAV pumps, and individual outlet power (Bulk Reef Supply 2024). The Pin Point pH Controller has fewer features as it only monitors pH and turns on and off the outlets on the controller (American Marine Inc 2024). This device is also not very user-friendly. There are also open-source projects available, but they lack many of the functionalities that professional systems have and rely on expensive instruments along with them (Onthank, et al. 2023).

Problem Definition (Qualitative Terms)

One solution that was proposed by Dr. Kirt Onthank in the biology department at Walla Walla University provides an alternative to the expensive machinery that is normally used to control and monitor the pH levels and temperatures of a controlled-tank environment. While this project was proposed by the biology department, it has now become a joint effort between many departments including biology, education, engineering, computer science, and product design.

The first collaboration occurred with the engineering department in 2018. Dr. Rob Frohne and Dr. Larry Aamodt, two electrical engineering professors, designed the hardware of the tank controller. Subsequently, Dr James Foster, Dr John Foster, Dr. Preston Carmen and students from the computer science department developed the software. The Computer Science Department continues to update the software on the tank controller to this day. Following the completion of the initial software, a product design student, JeruelRaj Razon with supervision from Prof. Jefre Humbert, created and refined the device’s housing. Lastly, Dr. Brian Hartman from the Education Department along with numerous students from this department have worked to create a version of this device suitable for use by high school students.

As a result of this interdisciplinary collaboration, the team at Walla Walla University was able to create an open-source research-grade device for less than \$250. This project is part of a larger group of projects known as the Open Acidification project. The Open Acidification project's mission is to provide a cost-effective open-source array of devices for ocean acidification research. The project focused on in this paper will be the redesign of the custom Printed Circuit Board (PCB) of the Open Acidification Tank Controller project as components used in the original tank controller are no longer available for purchase. This PCB serves to connect all the electrical components within the system.

Source of Project Idea

Building on the foundation of the original project, this new project will address the hardware limitations of the existing design. The original project is built on a microcontroller known as the Arduino Mega 2560. This microcontroller is now losing relevance as it is slower, more expensive, and has limited availability when compared to other options like the Raspberry Pi Pico 2 W. As a result, it's been decided to change the processor to a Raspberry Pi Pico 2 W. In the original design, the processor has many components attached to it such as a temperature sensor, a 4x4 keyboard, a Liquid Crystal Display (LCD), and an Ethernet shield. These components are correctly powered on because of a power management system that is made possible by something known as buck converters. These buck converters provide a regulated output voltage that is lower than the input voltage. Since the release of this open-source project, the buck converters on the PCB are not available for purchase anymore. There are also more hardware improvements that can be done on this device.

Problem Definition (Engineering Terms)

A new project arose from the current issue of the original tank controller project because the buck converters used in this project are no longer being sold to customers. This device uses two buck converters to step down our input voltage to safe and appropriate voltages for the device's components. These parts are very important and allow the device to function as intended. Now that they aren't available on the market, this project is no longer accessible to other organizations as they can't create the product anymore.

To combat these issues, a new plan will be developed to revive this open-source project. This senior project will consist of redesigning the current PCB using KiCad. One major goal will be to swap out the current 120V - 5V and 120V - 9V buck converters with an affordable, readily available, and reputable power supply module. The Arduino Mega 2560 will also be swapped for a Raspberry Pi Pico 2 W. This will allow more processing power especially when it comes to web-based applications. It will also lower our overall cost as the Pi Pico is much cheaper than the Arduino. The Pi Pico 2 W will also ensure this PCB's longevity as it is more readily available than the Arduino. Along with these changes, the client would also like to change the audio jack to a Bayonet Neill-Concelman (BNC) connector which is used for the temperature sensor. Another objective is to design the PCB with an emphasis on surface modules and components. This will simplify the process of assembling the board as many surface-mounted components can be soldered onto the PCB during manufacturing.

This extension of the original project will entail much more than just changing the Arduino, two buck converters, and making some small upgrades. When replacing a microcontroller with another, the transition requires more than simply swapping components for others. There are many things that will have to be changed from the current PCB. Figure 1 represents all of the components that are linked to the Arduino and how they are connected. One problem that arises when changing processors is the different number of pins and different input voltages. This project will also have to find a new Ethernet and SD card shield or similar component as this shield has been developed specially for the Arduino. Even if the buck converters were still available for purchase, they would still need to be changed as they would need to output different voltages to allow the new processor to run correctly.

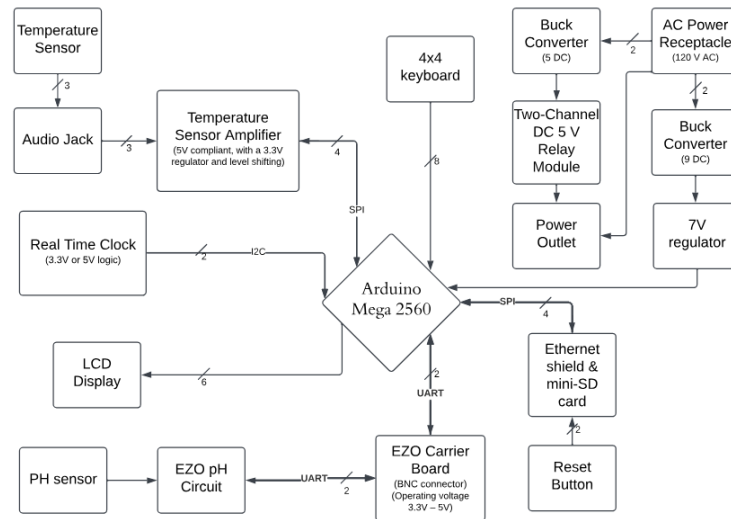


Figure 1. Original Tank Controller PCB Diagram (Cordova 2024)

Objectives

Design Criteria

One potential fix for the pin limitation is swapping out components like the 4x4 keyboard and LCD. These components use a lot of pins in comparison to the others (Figure 1). These parts also have variations of similar components that use a Serial Peripheral Interface (SPI) or Inter-Integrated Circuit (I2C) to communicate between them and the processor. Using components with these communication protocols would save wires as these protocols physically use fewer pins and can potentially share the bus. Another consideration when changing processors is the different input voltages they use. The Arduino Mega 2560 currently uses 7V for its input voltages (Figure 1), while the Pi Pico 2 W can operate in the range between 1.8V to 5.5V. This is more of an opportunity than a problem as this means in the new design there is also the possibility to eliminate the need for two buck converters and just use one 120V to 5V buck converter. The new and old processors also have different logic voltage levels. The Arduino runs on 5V logic, while the Pi Pico runs on 3.3V logic. After examining the logic voltages of all of the components on the device, it was discovered most of the parts support 3.3V logic so most components should be compatible. One component that will not directly work with the new processor is the ethernet and SD card shield. This device was created specifically for the Arduino

so a new solution is needed. After some digging, it was discovered that it is possible to buy a similar ethernet component hat for the Pi Pico 2 W.

With these new components, code will also need to be rewritten to allow the new parts to work. Coding will add too much scope to this project so there are two ways to proceed. Either the project can focus on just doing everything but a new processor or it can have sound hardware with a new processor and have someone else continue the code in the future. After some discussion with the client, Dr. Onthank, it was decided on the latter.

This project aims to meet all the performance requirements for the original project as well as add computational performance to the tank controller. The last project was required to have online parameter reporting with a user interface, hold data onto a micro-SD card for subsequent investigation, and lastly monitor and control pH and temperature (Onthank, et al. 2023). The Pi Pico 2 W offers significantly improved performance when compared to the original microcontroller, making it more suited to handle these tasks. The pH is controlled by adding CO₂ which is connected to one of the power outlets if the pH is above the configured value. Temperature is controlled by turning on a heater or chiller which is also connected to one of the power outlets depending on the desired temperature.

Codes and Standards

Codes and standards are very important in this project's design. For this reason, this project will focus on maintaining the standards that are outlined by the Institute for Interconnecting and Packaging Electronic Circuits (IPC) in IPC-2221. These standards were created as guidelines for PCBs and include electrical safety for them. This includes track sizes, electrical clearances, creepage, and routing (Jones 2004).

Constraints

This project's practical constraints are going to be what components are readily available on the market and buying them from a reputable supplier to allow supply longevity. There is also added practical manufacturing feasibility by having an emphasis on surface-mounted components that can be put on the PCB during production. All the components will also be obtained from reputable sources. A large restraint that the original project has is an economic constraint that should not pass \$250 as this is meant to be a cost-effective tool for ocean acidification research. As seen in Table 1, the total cost of the original project is \$202.13. This cost adheres to the budget constraint of remaining under \$250. This budget constraint will also be applied to this project. Additionally, safety constraints will also be put in place for this project. All the electrical designs will be configured to meet strict electrical safety requirements. Lastly, since this product is meant to be used by biologists and not engineers with technical electrical knowledge, a key constraint will be designing it to ensure simplicity to the end user during assembly.

Table 1. Cost Breakdown of Original Tank Controller Parts (Modified from Onthank, et al. 2023)

Component	Number	Cost per Unit	Total Cost
Elegoo Arduino Mega clone	1	\$17.49	\$17.49
KEYESTUDIO Ethernet shield	1	\$18.99	\$18.99
Adafruit MAX31865	1	\$14.95	\$14.95
PT100 Temp Sensor (3-wire)	1	\$12.98	\$12.98
1602 LCD	1	\$4.25	\$4.25
4x4 Keypad	1	\$1.50	\$1.50
2 Channel Relay Module	1	\$6.79	\$6.79
Adafruit PCF8523 Real Time Clock	1	\$4.95	\$4.95
Atlas Scientific EZO pH Circuit	1	\$41.99	\$41.99
Atlas Scientific Electrically Isolated Carrier Board	1	\$41.99	\$41.99
Power Receptacle	1	\$1.46	\$1.46
Power Outlet	2	\$1.15	\$2.30
3.5mm Jack Receptacle	1	\$1.30	\$1.30
5V AC DC Buck Converter Module	1	\$2.80	\$2.8
9V AC DC Buck Converter Module	1	\$2.36	\$2.36
Miscellaneous (ex. Resistor, Screws, etc.)	N/A	N/A	\$26.04
Total			\$202.13

Impacts

If this project was mass-produced and readily available, it would be useful in understanding and researching the effects of ocean acidification. As stated earlier, ocean acidification can have adverse effects on the ocean eco-system. By being able to research this topic more in depth at a lower cost, it can allow researchers to create plans to combat it and could also raise awareness. This is a positive impact but there can also be negative consequences. Once this device reaches the end of its life, it can contribute to plastic pollution if it is not disposed of accurately. This is because the tank controller's housing is made from 3D-printed plastic which can take years to decompose.

This project can also give students like those at Walla Walla University studying on the Rosario campus a better hands-on experience that will be used for years to come. By updating the PCB to have a more powerful processor, it can make the web-based experience more user-friendly. This project will also give access back to new students and researchers as it will have components that are in stock from reputable suppliers.

Globally, this project can allow more researchers access to professional testing equipment. This is because of its low cost but also its compact and portable design. This small size can allow this project to reach remote regions where a large device would be impractical to take.

Solution Alternatives

Four different microcontrollers from the Raspberry Pi Pico family were looked into for this project. The original Pi Pico came out in 2021 and took the world by storm with its powerful features, low price, and support from the Raspberry Pi community. The Pi Pico utilizes the RP2040 microcontroller chip, which has dual-core Arm Cortex-M0+ processor cores with a clock speed of up to 133 MHz. It also has 264kB on-chip SRAM and 2MB on-board QSPI flash (Raspberry Pi Foundation Oct 2024). The following year, the Pi Pico W was released, which included the Wireless capabilities (Raspberry Pi Foundation Oct 2024). Some time passed, and late last year, in 2024, the Pi Pico 2 and Pi Pico 2 W were released. The microcontroller chip in the Pico 2 and Pico 2 W use dual Arm Cortex-M33 or dual Hazard3 RISC-V processors with a clock speed of up to 150MHz. It also has twice the on-chip SRAM and QSPI flash, 520 kB and 4MB respectively (Raspberry Pi Foundation Feb 2024). After some back and forth between Dr. Onthank and Dr. James Foster, it was decided to use the Pi Pico 2 W. This decision was made for its added performance and built-in Wi-Fi. It also is almost entirely backward compatible with the original Pico as the Pico 2 W retains the same pinout functions and form factor. It does all of this while also being priced at \$7. The Raspberry Pi Pico 2 W also maintains constraints. This microcontroller will be manufactured for longer and is more affordable than the Arduino Mega 2560.

Design Development

Introduction to Main Components and Functionality

The new tank controller uses various different components to work including but not limited to a microcontroller, RTC, display, and sensors. At the heart of it, the tank controller uses the Raspberry Pi Pico 2 W as the microcontroller. This device is connected to peripherals to expand the functionality of a standard Pico. These devices are connected with respect to their communication protocols and the pin's functionalities, these protocols include I2C and SPI. A visual representation of the connections can be seen in Figure 2.

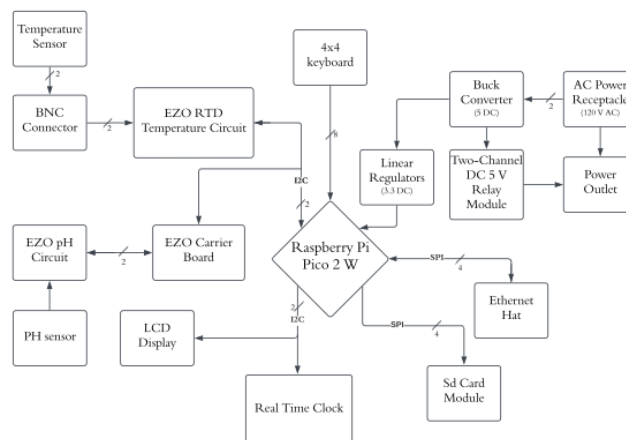


Figure 2. New Tank Controller PCB Diagram (Cordova 2025)

Reading pH and temperature are two crucial pieces of data for this project. For this reason, it is essential to read these values accurately. To do this, a reliable option was needed.

Therefore, the redesigned board will use temperature and pH circuit boards from Atlas Scientific. The temperature circuit has a sensing range of -126.000°C to $+1,254^{\circ}\text{C}$. The pH sensor has many features, including three decimal readings, calibration scope, extended range capability, immediate readings, timed readings, and multi-point calibration (Atlas Scientific Feb 2024). While these boards can communicate with either UART or I2C, I2C is the better option as the protocol allows devices to share the bus with others. Additionally, the pH sensor requires electrical isolation as it is a very sensitive device. This sensitivity is what allows the pH circuit's reading to be so accurate. To accomplish this electrical isolation, another component is required. This device, known as the Electrically Isolated EZO Carrier Board, has a female BNC connection on one end and pins on the other to communicate with the microcontroller. This component has headers on the board, which allow the pH circuit to connect to it and then output the signal through the pins. While the isolated board is needed for the pH sensor, it is not needed for the temperature sensor (Atlas Scientific Oct 2024). For this reason, it has been decided to connect a female BNC connector directly to the temperature circuit and route its output to the microcontroller. To measure the temperature of water, the sensor has been changed from a PT-100 to a PT-1000 to offer increased sensitivity and to allow compatibility with a male BNC connector. This temperature sensor also comes from Atlas Scientific, but any PT-1000 temperature probe with a male BNC connection will work.

Other devices that use the I2C protocol are the real-time clock (RTC) and LCD Display. The RTC is the same Adafruit component as the original tank controller. This peripheral allows the microcontroller to keep track of time even if the power is lost or reprogrammed (Adafruit 2024). Since this component is being reused, it should make programming simpler, as the same real-time clock code can be ported over. The LCD chosen is a 16 x 2 Chip-on-glass (COG) LCD (East Rising 2013) from BuyDisplay, a reputable online store. This component cuts down the pins used by the LCD from six to two.

The 4 x 4 keyboard is the same component as the original tank controller. This device was able to be reused as there were enough pins and this device can be found from reputable distributors as well. This keyboard allows users to input numbers zero to nine, letters A to D, an asterisk, and a pound sign (Parallax 2011).

Two devices use the SPI protocol: the Ethernet Hat and the SD card socket. The Ethernet Hat chosen was designed by Wiznet specifically for the Pi Pico. Thankfully, this device can also be used with the Pi Pico 2 W as it keeps the same footprint and uses the standard SPI protocol. At the heart of this Ethernet Hat is the W5100s chip, which is the successor of the W5100. The W5100 is the same chip used in the ethernet shield for the Arduino Mega 2560 (Wiznet 2018). This will allow the code from the existing repository for the ethernet functionality to work with slight modification. Like the Ethernet Hat, the SD card socket also uses the SPI protocol. This socket allows the microcontroller to read and write data to a micro-SD card.

The last components of the tank controller deal with power management. The new power management system consists of a power receptacle, 5V Buck Converter, two-channel DC 5 V relay module, linear regulator, and power outlets. The voltage starts at 120 V AC, and then the buck converter steps it down to 5 VDC for the two-channel relay. The two-channel relay is an electrically operated switch that allows the power outlets to be turned on and off. Going back to the buck converter, there will need to be another voltage step down. This time, the linear

regulator steps down the voltage from 5 V to 3.3 V. This voltage is supplied to the Raspberry Pi Pico 2 W and other components.

Overview of Design Activities and Analyses to be Done

Designing this PCB involved careful cost analysis. This is because the PCB redesign involves new parts, which have prices that can vary from the original design. The new estimated total is \$215.88, which is still within the budget constraints. A more detailed cost estimate can be seen in Table 2.

Table 2. Cost Breakdown of New Tank Controller Parts (Cordova 2025)

Component	Number	Cost per unit	Total cost
Raspberry Pi Pico 2 W	1	\$7.00	\$7.00
Atlas Scientific EZO RTD Temperature Circuit	1	\$35.99	\$35.99
Atlas Scientific Temperature Sensor	1	\$23.99	\$23.99
Ethernet Hat	1	\$4.95	\$4.95
SD Card	1	0.13	0.13
LCD	1	\$3.77	\$3.77
4x4 keyboard	1	\$9.36	\$9.36
Atlas Scientific EZO pH Circuit	1	\$45.99	\$45.99
Atlas Scientific Electrically Isolated Carrier Board	1	\$41.99	\$41.99
Power Receptacle	1	\$1.54	\$1.54
Power Outlet	2	\$1.15	\$2.30
BNC Connector	1	\$2.12	\$2.12
Buck Converter Module	1	\$7.99	\$7.99
2 Channel Relay Module	1	\$6.25	\$6.25
Real Time Clock	1	\$6.95	\$6.95
Miscellaneous (ex. Resistor, Headers, etc.)	N/A	N/A	\$15.56
Total			\$215.88

The design process for the PCB in KiCad will also require several key design activities. In this software, two of the biggest activities are creating the schematic diagram in the schematic editor and PCB planning in the PCB editor. In the schematic editor, the interconnections of the PCB are planned out. To do this, symbol parts must be imported, updated, or created to accommodate specific parts. Once the parts are placed and all the components are connected, electrical rules must be followed. KiCad has features to check if these rules are followed. Once this is checked, the PCB editor is populated according to the schematic and footprints associated with the symbols. Here, the footprints are places where they will be on the PCB and tracks are routed.

Design and Analysis of Components

The components were connected according to multiple constraints, including priority, available pins, and pin functionality. The first component to be accounted for is the Ethernet Hat. This is because this Hat is designed to sit on top of the Pi Pico, which means pins 21-22 & 24 – 27 need to be assigned to this device. Next, the Micro SD Module was assigned pins 14-17, which support the SPI1 instance. These devices were intentionally separated on independent buses for better performance, as the different SPI instances can operate independently. Once these assignments were made, the I2C connections were put into place, working within the remaining pin limitations. Finally, the 4x4 keyboard had connections mapped to the device. This device had low priority because it communicates to the microcontroller needing only GPIO pins. A more detailed table of the pin assignments can be seen in Table 3.

Table 3. New PCB Pin Assignments (Cordova 2025)

Pin #	Functions				Device 1	Connection	Device 2	Connection
1	GP0	SPI0 RX	I2C0 SDA	UART0 TX	Debugging header	UART_TX		
2	GP1	SPI0 CSn	I2C0 SCL	UART0 RX	Debugging header	UART_RX		
3	GND							
4	GP2	SPI0 SCK	I2C1 SDA		4x4 keyboard	ROW1		
5	GP3	SPI0 TX	I2C1 SCL		4x4 keyboard	ROW2		
6	GP4	SPI0 RX	I2C0 SDA	UART1 TX	PH Carrier Board	Sensor_SDA	Temp Circuit	Sensor_SDA
7	GP5	SPI0 CSn	I2C0 SCL	UART1 RX	PH Carrier Board	Sensor_SCL	Temp Circuit	Sensor_SCL
8	GND							
9	GP6	SPI0 SCK	I2C1 SDA		4x4 keyboard	ROW3		
10	GP7	SPI0 TX	I2C1 SCL		4x4 keyboard	ROW4		
11	GP8	SPI1 RX	I2C0 SDA	UART1 TX	4x4 keyboard	COL1		
12	GP9	SPI1 CSn	I2C0 SCL	UART1 RX	4x4 keyboard	COL1		
13	GND							
14	GP10	SPI1 SCK	I2C1 SDA		Micro SD Module	SD_CLK		
15	GP11	SPI1 TX	I2C1 SCL		Micro SD Module	SD_MOSI		
16	GP12	SPI1 RX	I2C0 SDA	UART0 TX	Micro SD Module	SD_MISO		
17	GP13	SPI1 CSn	I2C0 SCL	UART0 RX	Micro SD Module	SD_CS		
18	GND							
19	GP14	SPI1 SCK	I2C1 SDA		LCD	SDA_Peripherals	RTC	SDA_Peripherals
20	GP15	SPI1 TX	I2C1 SCL		LCD	SCL_Peripherals	RTC	SCL_Peripherals
21	GP16	SPI0 RX	I2C0 SDA	UART0 TX	Wiznet Ethernet Hat	SPI0 RX		
22	GP17	SPI0 CSn	I2C0 SCL	UART0 RX	Wiznet Ethernet Hat	SPI0 CSn		
23	GND							
24	GP18	SPI0 SCK	I2C1 SDA		Wiznet Ethernet Hat	SPI0 SCK		
25	GP19	SPI0 TX	I2C1 SCL		Wiznet Ethernet Hat	SPI0 TX		
26	GP20		I2C0 SDA		Wiznet Ethernet Hat	RSTn		
27	GP21		I2C0 SCL		Wiznet Ethernet Hat	INTn		
28	GND							
29	GP22				Relay	Relay_IN1		
30	RUN				Reset Button	RESET		
31	GP26	ADC0	I2C1 SDA		4x4 keyboard	COL3		
32	GP27	ADC1	I2C1 SCL		4x4 keyboard	COL4		
33	GND	AGND						
34	GP28	ADC2			Relay	Relay_IN2		
35		ADC_VREF						
36	3V3(OUT)							
37	3V3_EN							
38	GND							
39	VSYS							
40	VBUS							

GND
GPIO, PIO, PWM
System Control
I2C
I2C (default)
SPI
SPI (default)
ADC
UART
UART (default)

With the pin assignments established, the next step was to design the schematic to properly connect all components. When completing a schematic, wires can't just be connected to the pins of the microcontroller. Detailed research has to be completed to connect the devices. This ensures the device's functionality and longevity. Figure 3 illustrates the complete schematic, detailing how each device interfaces with the Pi Pico 2 W.

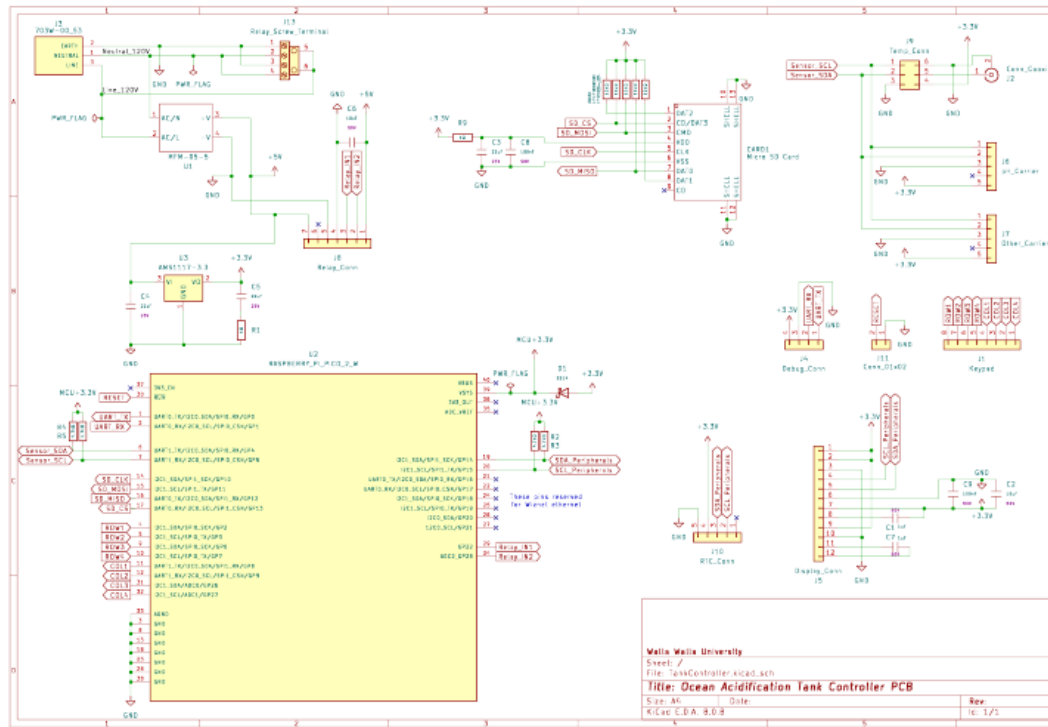


Figure 3. New Tank Controller Schematic (Cordova 2025)

To create the power management system, a power receptacle (702W-00/53) is used to feed power into the system. This receptacle has earth, neutral, and live line connections. The neutral line and live line are then connected to the buck converter (MFM-05-5), which steps down 120V to 5V. This 5V powers the relay module as well as the linear regulator (AMS1117-3.3). The linear regulator will adjust the voltage from 5V to 3.3V and power the rest of the components in the PCB. It's also important to note the screw terminals connect the earth and neutral lines to the power outlet on the tank controller box. The live line connection goes to the relay module, which then connects to the outlets. This is done so the relay can control the flow of power to the outlets, allowing it to switch connected devices on and off as needed.

Components that use the I2C protocol share a common bus, with the temperature and pH sensor on one bus and RTC and display on another. Figure 3 also shows the display with capacitors and resistors connected to it. These components are connected according to the recommended schematic provided by the distributor. There are also pull-up resistors on each one of the data lines as a conservative approach. While the Pi Pico 2 W includes internal pull-up resistors, the effectiveness of these resistors is called into question in the RP2350 Erratum E9 (Raspberry Pi Foundation 2025).

The SD card socket uses ten-kilo ohm pull-up resistors on five pins as specified in the official SD card standard (SD Card Association 2023). For the power, two capacitors in parallel and a series resistor have been added to keep the device safe. This is done as without it when a card is plugged in and the device powers on, there will be an inrush of current that can cause brownouts.

The Ethernet Hat is also accounted for in the schematic seen in Figure 3. While it doesn't appear as a physical component on this schematic, the designated pins remain unconnected to anything else. This ensures if the Hat is installed, it can function without interference or conflicts with other devices. This device may be problematic as the device already has Wi-Fi capabilities. This component is included in the design as many institutions have very sophisticated and strict Wi-Fi protocols that will not allow devices like the Pi Pico to connect to it. While this is a valid concern, the Walla Walla University IT department has confirmed they can accommodate this feature. Accommodations include connecting to the network directly on their end using the Pi Pico's MAC address or giving the Biology Department a hotspot that will allow this connection. Wi-Fi capability is a valuable option for added flexibility. Having a wireless connection gives the department greater mobility, making it easier for the tank controllers to be relocated and the system to be expanded without additional cabling.

The schematic also includes a debug header that will be used for testing and a reset header that connects to the RUN pin. When this pin is shorted to ground, the RP2350 is reset, causing the Pi Pico 2 W to restart the program's execution (Raspberry Pi Foundation 2025). This acts as a simple reset for the tank controller. The keypad is also connected using the Keypad socket. This socket has four inputs and four outputs.

The Pi Pico 2 W also requires a 3.3V power supply and it is crucial to follow specifications when powering the microcontroller, as a mistake here can ruin the design. This microcontroller will possibly be connected to two power sources simultaneously, which can damage it. This can occur when one of the power input pins is connected to a 3.3V and the USB connector is also being used. To combat this, the Pico 2 W's datasheet suggests to "the simplest way to add a second power source to Pico 2 W is to feed it into VSYS via another Schottky diode" (Raspberry Pi Foundation 2025). This solution allows for safe dual power inputs, ensuring the microcontroller receives stable and protected power from both sources without risk of damage.

With this, the schematic was complete, and the PCB design was started. The first thing that was done was to create footprints for every component that would be placed on the PCB. Footprints are used to define the physical connections and dimensions of a component. These footprints were then assigned to components in the schematic which allowed the PCB editor to be populated. In the PCB editor, the first thing that was done was to decide on the general placement of the device's components. This is an important step as large changes in the PCB layout after the tracks are placed can result in much more time fixing the issue than if it were caught earlier. Some components took priority to be on the front of the board as they needed to be accessed facing upwards or oriented upwards. These components include the display, 4x4 keypad, BNC connectors, Pi Pico 2 W, Two Channel Relay Module, and all surface-mounted components. The display and 4x4 keyboard play a critical role in inputting and viewing data from the Tank Controller. For this reason, it was important that they were at the front of the board, to allow for easy access to their functionalities. The BNC connectors were required to be on the top of the PCB to allow for the standard orientation of these components. Another component that was decided to be on the top of the board is the Pi Pico 2 W. The Pi Pico is the microcontroller board that can normally be placed in any orientation or side, except in this design. This is because this new design involves an Ethernet hat that has been configured to be stacked on top of the Pico. Continuing down the list, the Two Channel Relay Module was also

on the list for ease of assembly. This module has screw terminals where power comes in and out and the components it connects to are on the top of the board. If this component were on the back of the board, longer wires would need to be run which would make the board assembly more difficult. Lastly, surface-mounted components were required to be on the top of the board, as when the board is manufactured, it is cheaper to have all of these components on one side.

The second thing taken into account is whether the components need to be on the edge of the board. Components needing to be close to the edge include the BNC connectors, power receptacle, Pi Pico 2 W, and reset button. More specifically, the reset button was requested by the client to be all on one edge of the board. The client also proposed a stretch goal of adding a third BNC connector for an additional sensing circuit, such as the dissolved oxygen circuit by Atlas Scientific. This request was accommodated for as sufficient space was available and was made possible as the I2C protocol shares the bus with the other sensing circuits. Once these component placements were decided, other components were placed as space became available.

Component orientation was also an important factor in this PCB. The SD card needed to be oriented in a way that would not impede a micro-SD card from being inserted. The two-channel relay was also required to face certain components to allow for simple cable management. Lastly, the screw terminals were placed to face the edge of the board to allow for easy connection to the power outlets. Figure 4 shows the front side of the PCB with the components placed on it for reference and more clarification.

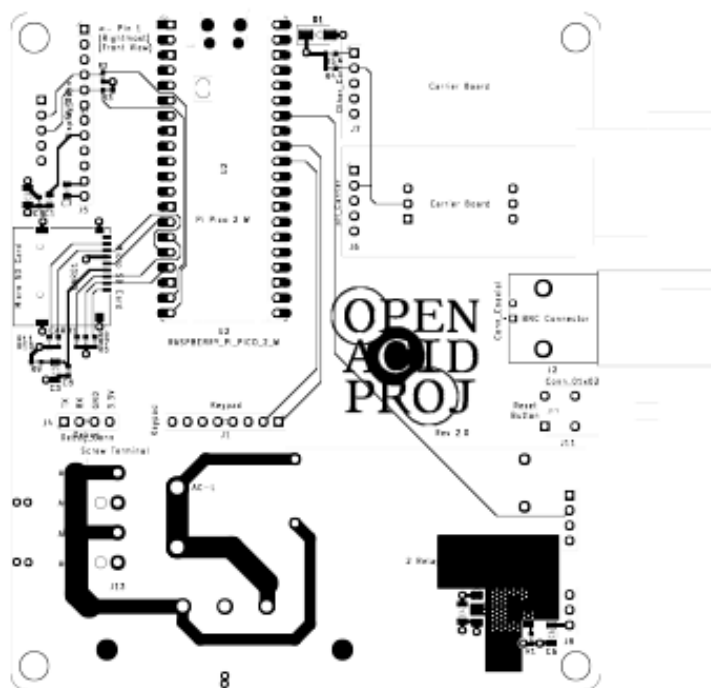


Figure 4. New Tank Controller Front Layout (Cordova 2025)

The components on the backside of the PCB include the buck converter, temperature circuit, real-time clock, and power receptacle. These components offer more flexibility and were able to be placed on the back. While the side of the PCB was not critical for these components,

the location still is. The receptacle needed to be positioned on the edge of the board so the buck converter was placed around it to minimize long, high-power traces and reduce potential voltage drops. Similarly, the temperature circuit and real-time clock were also positioned close to the Pi Pico 2 W to minimize signal degradation and ensure reliable I2C communication. These components can be seen in more detail in Figure 5.

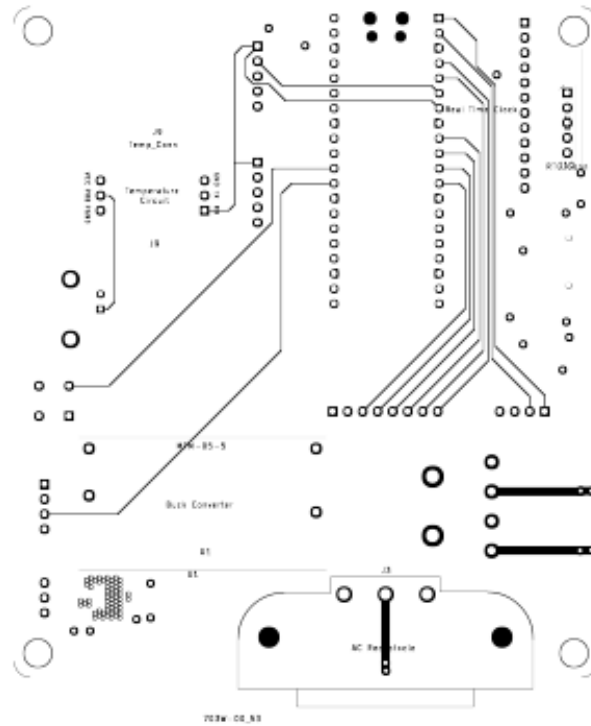


Figure 5. New Tank Controller Back Layout (Cordova 2025)

With the components placed, the PCB was designed to use four layers. This configuration allows for simpler routing of tracks as the top and bottom layers are dedicated to signals and the middle layers are reserved for power and ground planes. This also enhances thermal performance for components with lots of heat to dissipate. This is achieved with thermal vias connected to the power plane around the linear regulator output to help distribute and dissipate heat more effectively. This can be seen in Figure 4. Additionally, this four-layer configuration can also help reduce electrical noise and enhance overall signal integrity.

Tracks and vias were placed according to electrical safety standards. IPC-2221A outlines these standards including minimum spacing for electrical conductors. These spacing requirements can be observed in Table 4. Traces routed on the PCB fall under the B3 column as they are on the top or bottom of the board, considered uncoated, and the elevation is uncertain.

Table 4. IPC-221A Electrical Conductor Spacing Standard (IPC 2003)

Voltage Between Conductors (DC or AC Peaks)	Minimum Spacing						
	Bare Board				Assembly		
	B1	B2	B3	B4	A5	A6	A7
0-15	0.05 mm [0.00197 in]	0.1 mm [0.0039 in]	0.1 mm [0.0039 in]	0.05 mm [0.00197 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]
16-30	0.05 mm [0.00197 in]	0.1 mm [0.0039 in]	0.1 mm [0.0039 in]	0.05 mm [0.00197 in]	0.13 mm [0.00512 in]	0.25 mm [0.00984 in]	0.13 mm [0.00512 in]
31-50	0.1 mm [0.0039 in]	0.6 mm [0.024 in]	0.6 mm [0.024 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.4 mm [0.016 in]	0.13 mm [0.00512 in]
51-100	0.1 mm [0.0039 in]	0.6 mm [0.024 in]	1.5 mm [0.0591 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.5 mm [0.020 in]	0.13 mm [0.00512 in]
101-150	0.2 mm [0.0079 in]	0.6 mm [0.024 in]	3.2 mm [0.126 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
151-170	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	3.2 mm [0.126 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
171-250	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	6.4 mm [0.252 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
251-300	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	12.5 mm [0.4921 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.8 mm [0.031 in]
301-500	0.25 mm [0.00984 in]	2.5 mm [0.0984 in]	12.5 mm [0.4921 in]	0.8 mm [0.031 in]	0.8 mm [0.031 in]	1.5 mm [0.0591 in]	0.8 mm [0.031 in]
> 500 See para. 6.3 for calc.	0.0025 mm /volt	0.005 mm /volt	0.025 mm /volt	0.00305 mm /volt	0.00305 mm /volt	0.00305 mm /volt	0.00305 mm /volt

B1 - Internal Conductors

B2 - External Conductors, uncoated, sea level to 3050 m [10,007 feet]

B3 - External Conductors, uncoated, over 3050 m [10,007 feet]

B4 - External Conductors, with permanent polymer coating (any elevation)

A5 - External Conductors, with conformal coating over assembly (any elevation)

A6 - External Component lead/termination, uncoated, sea level to 3050 m [10,007 feet]

A7 - External Component lead termination, with conformal coating (any elevation)

One notable trace of this Tank Controller handles 120V Root Mean Square (RMS) that comes from the power receptacle. This voltage is alternating which indicates it has a peak voltage higher than the RMS voltage. In this case, the approximate peak voltage is 170 V. When analyzing Table 4, it can be determined that the minimum spacing for these traces is 3.2 mm. This clearance was added around traces in order to prevent creepage.

Manufacturing

The PCB files were sent to be manufactured by PCBWay, a large Chinese company that specializes in PCB prototyping. This company is reputable and provides a service that is well-priced. This company provides surface-mounted assembly for components that it stocks. This improves the ease of assembly on the consumer's end by placing and soldering surface-mounted components. Once the PCB boards were in hand, the through-hole components were soldered on. While all of the through-hole components can be directly soldered onto the PCB, headers were chosen for most of them to allow for simple and quick swap-outs. A notable through-hole component that was soldered directly onto the PCB was the buck converter. This is because the pins are irregularly spread apart and require four 1x1 headers, which raised concerns of mechanical stability and the strength of the pins.

Testing

Testing was also required for this board to ensure the component's functionality. In this testing, there were two categories: hardware and software testing. Before anything was done, the board went through a physical inspection. This was done to ensure there was no damage to the board during shipping, as well as to check the correct component placements. Next, key traces were checked for continuity with a handheld multimeter. This was done to high-power traces as well as connections to peripherals. Once this was verified, the linear regulator was soldered onto the board, and the power was checked on the traces. The buck converter's input and output, the linear regulator's output, and the 3.3V and 5V traces were checked for their corresponding voltages. The voltages were verified using a Fluke 8846A 6-1/2 Digital Precision Multimeter. After this test was passed, the rest of the components were soldered onto the board, and the software testing began.

Software testing was accomplished to ensure the tank controller's basic functionality. The programming was done on VS Code using the PlatformIO extension. First, the functionality of the Pi Pico 2 W was tested to ensure programming was possible. This was done by setting the Pico 2 W into BOOTSEL mode and programming the on-board LED to flash on and off. Once the ability to program was successful, the peripherals were next.

The first peripheral to be tested was the pH circuit. The chosen pH circuit's default protocol is UART which means it needed to be changed to I2C. For this, the data sheet describes disconnecting the circuit, shorting the TX and PGND pins, and then powering on the PH circuit (Atlas Scientific Feb 2024). Once the LED is shorted, the circuit will verify the protocol by changing the onboard LED from solid green to blue. With this manual protocol switch, the I2C address is set to 0x63. After enabling the I2C protocol, basic code was used to prove the functionality by reading the pH of distilled water. Very similar steps were taken to ensure the functionality of the temperature circuit, except the TX and PRB lines were shorted which set the I2C address to 0x66 (Atlas Scientific Oct 2024). The functionality of the temperature circuit was tested at room temperature. Both the pH and temperature circuits were programmed using the Wire library by Arduino and the Ezo_I2c_lib library by Atlas Scientific, which is designed for using EZO devices in I2C mode.

Next, the SD card functionality was tested using the SD and SPI libraries by Arduino. Using these libraries, the Pi 2 W was able to write a test text file to the micro-SD card. Code was also developed to verify the relays, whose operation was confirmed with an audible click noise when switched. The keypad used very similar code as the original tank controller with some additional code for debouncing. The real-time clock was programmed using the Wire library by Arduino and the RTCLib library from Adafruit, which kept time even when the tank controller PCB was not being powered on. Programming the LCD also required the Wire library and another known as LCD_ST7032. With this library, the text "Hello World" and "LCD @0x3E" were written on the first and second lines of the display, respectively. Unfortunately, the Ethernet hat could not be programmed as it was incorrectly placed onto the Pi Pico 2 W when testing first began. This improper placement caused the component to emit smoke, rendering it nonfunctional. This did not significantly impact the project as the Pi Pico 2 W includes built-in Wi-Fi functionality.

Evaluation of the Project

This project set out to accomplish various tasks, including changing the Arduino Mega 2560 to a Raspberry Pi Pico 2 W, designing the board with a new power supply from a reputable company, replacing the audio jack with a BNC connector, and designing this project with an emphasis on surface-mounted components. With these changes, a series of constraints also had to be considered. These constraints include, but are not limited to, both physical and monetary restrictions.

Changing the microcontroller to the Pi Pico 2 W required physical constraints to be dealt with, including pin limitations, as the Pico has fewer pins than the Arduino Mega 2560. To combat this constraint, various components were swapped out for their I2C counterparts. This new microcontroller board also required 3.3V for power instead of the 5V from the last board. This constraint went hand in hand with one of the new power supply tasks. The improved power supply consists of one 120V to 5V buck converter to power the two-channel relay and a linear regulator to step down the voltage to 3.3V for the rest of the components. It's important to note that the buck converter chosen is from a company known as MEAN WELL. This company is a well-established company whose purpose is to produce power supply products. They also have a very good track record of supply longevity. Changing the audio jack to a BNC connection was also able to be accomplished by using a new temperature sensor and circuit. This board was also designed with surface components where applicable to allow for simplicity to the end user.

Monetary constraints for this project included keeping the project under \$250. This is very important as it is meant to be a cost-effective solution to the high prices of traditional ocean acidification research equipment. As seen from Table 2, the new estimated pricing for all the components of this PCB is \$215.88 which means this constraint has been met.

Other constraints of this project include practical and safety restrictions. This project was designed with simplicity to the end user in mind, so the placement of the components had to be practical. Examples of this include positioning components in places that would simplify assembling the Tank Controller, as well as placing all components that stick out of the board on one side. This allows users to have less to worry about when they place the tank controller in a bag for transport. Electrical safety restrictions outlined in IPC-2221A were also followed. The most important standard followed was the minimum electrical conductor spacing to avoid electrical creepage.

This project has the opportunity to have environmental, societal, and global impacts. This project can help researchers better understand the effects of ocean acidification as it lowers the barrier to entering the field by offering a cost-effective solution. This can also raise awareness of the issue as more people can get involved with this matter. When this device reaches the end of its life, certain components can be recycled for other projects or discarded. This can cause pollution in the environment, which can harm different habitats around the world. Students can benefit from this design by having a modern piece of equipment that can provide hands-on experience. This can strengthen their understanding of real-world challenges and critical thinking skills. Globally, more researchers with a limited budget will be able to access professional testing equipment.

Conclusions

This project successfully solved the main problem with the original tank controller by addressing its main problem by changing components that were obsolete or discontinued for more standard parts from reputable sources that will have supply longevity. This was accomplished while also following constraints and standards. Additionally, a stretch goal was also achieved by adding a third spot for an additional sensing circuit, like the dissolved oxygen circuit by Atlas Scientific. One functionality not able to be tested was the Ethernet functionality as the board was improperly placed onto the Pi Pico, causing it to fail. Although a setback, the Ethernet hat was not critical to the tank controller. By completing this project, students and researchers can study the effects of ocean acidification without the high price of conventional machinery.

Future Work

While this project focused on the hardware aspect of the new tank controller, there is still much more work to do on the software side. During testing, the basic functionality of the components was established, but a fully developed software project is still required to enable researchers to simply use the new tank controller without needing to manually configure or program the system. Additionally, the new tank controller also needs a new enclosure as the new PCB has different dimensions than the original as well as different placements for connectors.

While testing this board, several potential hardware improvements were identified. The display jumper cable that was ordered has 2.56 mm header spacing which is common for electronic components however the display pins use 1.80 mm spacing. This change might seem small, but this difference in spacing doesn't allow for the display to be connected to the jumper cable. For testing purposes, the jumper cables were directly soldered onto the display, which proved the functionality of the LCD, but isn't practical for someone with little experience in soldering. After an extensive search, no jumper cables were found that fit the display's specifications. With this information in mind and in consultation with the client, Dr. Onthank, a recommended display moving forward is the 3.3V HD44780 Display Module with I2C adaptor board which can be bought from many different sellers, including BuyDisplay. This module still uses I2C so the swap should be seamless, but new code will be required. Additionally, the BNC connectors can be moved slightly outward so that the force applied during connection or disconnection is transferred onto the future housing rather than the pins holding them up. Lastly, the Ethernet hat can be placed directly onto the PCB, as the correct orientation on top of the Pi Pico 2 W has the Ethernet connector facing the inside of the board rather than the outside. This causes limited accessibility to the port and interferes with the 4x4 keyboard connection.

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