Year Three

Midterm Report

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Abstract

Waterlab is a water purification technology built to provide enough usable drinking water to sustain the daily intake requirements of around nine hundred individuals. Our system features multiple internal filter components that can successfully clean water up to the EPA drinking standard to ensure quality water for its users. Waterlab is also an off-grid system powered solely by renewable energy technologies to ensure functional longevity and environmental sustainability. This allows our system to operate at any time of the day or night. Lastly, our system contains an easy to use interface built on top of an autonomous control system to make our system responsive for the user and reactive to errors. This technology has been implemented to provide a portable solution for the lack of clean drinking water experienced by the large group of unfortunate communities that still exist in our world today.

WaterLab 3.0 Purpose

The purpose of waterlab is to provide a reliable source of EPA standard[1] drinking water for communities located off-grid. EPA standards provide list of maximum levels of water contaminants for safe drinking in the United States. Waterlab will be implemented in communities off-grid, and is able to be self powered through photovoltaics as well as a permanent magnet DC generator. These power sources will allow the system to potentially run continuously throughout the day, allowing the filtration and disinfection of enough water to sustain the two liter intake requirements of upwards of nine-hundred individuals a day. This section will provide the background and overview needed to understand the motivation for our project, the problems that WaterLab attempts to solve, and known issues that we have come across throughout the engineering and design process.

The purification process[2] of water treatment centers go through three stages, each removing a form of contaminant from a water supply. Primary water treatment removes the sludge and debris from the water, allowing most of the particulates to be removed. The next two stages are what waterlab covers, which involves the use of filters and a biological deactivation ultraviolet light component. Waterlab cannot purify raw sewage, but it has been designed to handle the purification of secondary effluent.

Framing the Problem

Electrical power grids are a convenience that many developed regions of the world have come to take for granted. The same can be said of purified water systems. The infrastructure and resources required to have publically available potable water, and a reliable power source are oftentimes unattainable for rural locations or impoverished regions around the world. Even though most countries in our world have acquired electricity and water purification technologies, there still remains many regions where less than twenty percent of the population have access to these two commodities.[3] The lack of access to purified water carries severe health consequences for these unfortunate communities.

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[1] For more information on EPA standards visit the website: https://www.epa.gov/dwreginfo/drinking-water-regulations

[2] For more information of the specific treatment of wastewater treatment plants, visit the EPA website: https://www3.epa.gov/npdes/pubs/bastre.pdf

[3] Information statistics for electrical access: https://data.worldbank.org/indicator/eg.elc.accs.zs
Information statistics for water access: https://data.worldbank.org/indicator/SH.H2O.SMDW.ZS

Water purification can be an energy hungry[4] process on a large scale, requiring up to five watt-hours of power for each gallon purified in California. The power requirement for purification becomes quite large when speaking in terms of Mega-gallons[5] of water each day. Using California as an example again, California consumes anywhere from six to nineteen billion watt-hours of power a day for waste water purification. For perspective, this equates to powering fifty million homes[6] a day in California. Although these numbers will vary state to state, the daily energy demands of waste water purification is quite large.

Potable water, according to the Environment Protection Agency (EPA), needs to meet all of the following standards:

- **Turbidity**: This is a measure of the clarity of the water. Turbidity can affect the effectiveness of UV disinfection and is an indicator for the presence of suspended algae or sediments. Turbidity is measured in units of Nephelometric Turbidity Units (NTU).
- **Total Dissolved Solids (TDS) [<500ppm]**: TDS is one of the most basic measurements of water quality; high concentrations of dissolved solids in water are possibly, but not necessarily, harmful. Our TDS should theoretically be very low due to the sediment pre-filter with 1 micrometer mesh.
- **Specific Conductivity (SC) [<1055μS]**: SC is the measurement of electrical conductivity for a water sample and can also be used to estimate the amount of dissolved solids in water, as it measures the dissolved ionic compounds in the water. We will be able to continuously monitor the conductivity using sensors (μS·cm-1).
- **Bacteria**: In order to assess the danger of bacterial contamination to humans, fecal coliforms are typically used as an indicator species. If a large number of coliform bacteria (over 200 colonies/100 ml of water sample) are found in water, it is assumed that pathogenic (disease- or illness-causing) organisms are also present in the water. This is certainly a concern when filtering secondary-treated wastewater, as we plan on doing.
- **Arsenic**: Arsenic is highly toxic. Chronic exposure even at relatively low doses over many years could experience skin damage or problems with their circulatory system, and may have an increased risk of getting cancer.
- **Fluoride [<2ppm]**: In low concentrations, it is used as an additive in the US municipal water supply to strengthen tooth enamel. At drinking water concentrations above 2 mg/L, it may cause aesthetic effects such as enamel or dental fluorosis (mottling or discoloration of tooth surfaces). At higher concentrations (generally thought to be above 4 mg/L), it may cause more severe forms of enamel fluorosis (pitting of tooth surfaces), as well as skeletal fluorosis, a debilitating condition that may involve bone deformation and brittleness.
- **pH [6.5-8.5]**: This is the measure of the acidity/alkalinity of the water. A pH range between 6 to 8.5 is considered normal for drinking water.
- **Color**: Water discoloration is a good indicator that, simply, something isn't quite right but may not be directly correlated with a health concern. Color is generally measured in Color Units.
- **Alkalinity/Hardness**: Alkalinity is the ability of a water sample to neutralize acids, as measured by the amount of alkaline compounds in water, such as carbonates (CO3 2-), bicarbonates (HCO3-), hydroxides (OH). Hardness is the concentrations of metal ions (generally calcium and

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[4] Power requirements estimated using wastewater energy required for purification taken from: https://www.home-water-works.org/energy-water

[5] For more information on the wastewater system in California reference the following site: https://www.watereducation.org/sites/main/files/file-attachments/lpg_wastewater_abridged.pdf

[6] For average power consumption of a home in California reference: https://www.electricchoice.com/blog/electricity-on-average-do-homes/

magnesium carbonates) in the water. It is not generally a health problem, but rather a consumer concern.

- **Dissolved Oxygen**: Dissolved oxygen can give an indication of the general health of a water supply. Low dissolved oxygen (anaerobic) environments can indicate the presence of naturally occurring sulfur-reducing bacteria that can create a "rotten egg" smell in the water as well as a slime that can clog pipes and pumps. This can also indicate the presence of decomposing organic material in the water.
- **Iron [<0.3ppm]**: Iron in drinking water does not pose a human health risk, but high iron concentrations can be unpleasant tasting; certain types of bacteria are also attracted to iron, which may lead to a slime or sludge generated by the bacteria that has an offensive odor and can plug treatment systems or pumps; and iron can reduce the efficiency and effectiveness of UV disinfection.
- **Nitrites [<1ppm] /Nitrates [<10ppm] /Ammonia**: The presence of Nitrogen compounds, even at low concentrations, pose health risks for humans and wildlife. High concentrations, especially, are indicators that nitrifying bacteria colonies may be present in the treatment system. Ammonia is a naturally occurring inorganic nitrogen form whose presence may be caused by sewage effluent, agricultural runoff, feedlot drainage, industrial discharge, or desorption from natural deposits.
- **Phosphates [<0.025ppm]**: High levels of phosphate can overstimulate the growth of aquatic plants and algae resulting in low dissolved oxygen levels.
- **Chlorine[<4ppm]**: Chlorine disinfection is common for tertiary-treated water specifically, but also used in other stages of water treatment. If not properly removed from the water during treatment, high concentrations of chlorine pose health risks.

Proposed Solution

Waterlab has been designed to be portable, sustainable, and reliable to provide a solution for the misfortunes faced by many impoverished communities. Portability was chosen as a requirement since Waterlab is expected to be used in communities with various water source types. Water sources can change subtly throughout the year, such as the inundation of a river or lake, and therefore the placement of watlab must be flexible and moveable. For sustainability, Waterlab was engineered to have maintenance guidance, renewable energy sources, and long lasting internal components. Lastly, reliability is satisfied through the use of system error checking achieved from the integration of a diverse group of sensors and displaying diagnostics. Waterlab minimizes user involvement unless maintenance is required, allowing for simplicity and reliability. We have designed this project to fulfill many engineering requirements[7] and specifications according to our vision for WaterLab's future.

The creation of an off-grid, renewable energy water filtration system comes with its own challenges. In order to provide consistent water filtration, the first challenge for an off grid system is developing a method to produce reliable energy for the filtration system at all times. The design must have a properly-sized energy storage bank as well energy production methods sufficient enough to allow the system to run continually with minimal user interaction. Our system will overcome these obstacles by utilizing daytime solar energy acquired using solar panels. In order for our system to generate energy when sunlight is not accessible we have also integrated a mechanical power generating bicycle pedal for the user to use when additional energy is needed.

As a solution to the lack of access to reliable, potable water, our project proposes to create a water filtration and disinfection system operate with minimal user involvement, and provide system diagnostics for easy maintenance through the use of a user interface. WaterLab will implement a power system that is able to generate and store enough energy to continuously filter throughout the day. To

[7] Reference Appendix A for a list of requirements we imposed on Waterlab

gauge potability, our team has decided to use the EPA standards for water purity used in the United States. The power input from these two sources are stored into batteries that are appropriately sized for continuous operation.

To resolve issues that stem from outdoor deployment of a mobile filtration system, WaterLab has been built with certain specifications. To be more portable, the WaterLab device has been affixed with heavy duty wheels, and a strong aluminum frame. The aluminum frame securely affixes the filtration components while also providing structural integrity for safe transportation. Components of the WaterLab system have been chosen for maximum corrosion resistance against damp or humid climates, and has an outer wall to prevent UV and water damage to system components.

To overcome the difficulties that result from continuing projects, we have spent significant time on efficient and useful documentation, undergone thorough investigations on design requirements, and decided on a well defined scope for this project. To prevent scope creep, our team has decided to implement the water purification system to pretreated water or river water with pre screened water intake.

Known Difficulties

Projects that tend to continue over multiple generations of design teams often suffer from common pitfalls such as insufficient documentation and scope creep. One common issue that occurs in continuing projects is the lack of documentation for explicit descriptions of design choices. Not only do continuing teams have problems with aligning perspectives on design, they also can bring new ideas into the project, resulting in wasted time and resources through scope creep[8]. Therefore, teams that take up this project should be diligent with documentation, efficient design, sound reasoning, and a well defined scope.

Any project, no matter how well planned, has potential to fall to known system difficulties that can result in discontinued operation. The main difficulties that we will face pertain to improper use and care of the WaterLab system. We aim to overcome these known difficulties through a well documented set of operating procedures and user manual documentations. These documents will describe proper procedures for maintenance, system setup, and component testing. Additionally, subtle difficulties may arise in regards to external sources such as whether and climate. These difficulties were harder to plan for, but solutions are attempted as they arise.

The solution path that WaterLab takes to implement offgrid energy results in the need for battery maintenance as well as the handling of high voltage power lines during times of transportation. We address these issues through the user manuals provided, and we emphasize that the user follow testing procedures closely as laid out in SOP documentations as well as pay close attention to advice given in regards to safety, proper component handling and maintenance, and lessons learned.

The WaterLab filtration system is prone to failure if filter replacement regimens are not followed, or if other system diagnostics are ignored. Our users manual provides information on water quality testing, filter replacement, and sensor replacement and calibration, but an issue that we have yet to resolve is the proper timeline for filter replacement with respect to high levels of continuous water contamination density. The user is advised to follow water testing regimens often to have early warnings of filtration failures to avoid water borne illnesses.

The WaterLab electrical system is sensitive to flood waters. Due to the desired implementation of WaterLab, it is a likely scenario that WaterLab will be positioned near sources of water that have potential for inundation or flooding. As a team, we attempt to solve flooding issues through frame design as well as fault protection in cases of shorted power lines.

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[8]Scope creep is a problem that affects many projects. For more information on this phenomenon see the following:
Top causes of scope creep - https://www.pmi.org/learning/library/top-five-causes-scope-creep-6675
General information of what scope creep is - https://en.wikipedia.org/wiki/Scope_creep

The WaterLab system is nearly 500 lbs, which carries many negative implications including crushing hazards. Placing the WaterLab system on a slope is hazardous, so proper care and placement of the system is crucial. Elaborate safety instructions can be found in our users manual.

System Overview

To understand how Waterlab works, we can break it down into four essential subsystems. The three essential subsystems that pertain to the filtration process itself are the power subsystem, water filtration subsystem, and the control subsystem. **Figure 1** shows the generalized overview of these three subsystems.

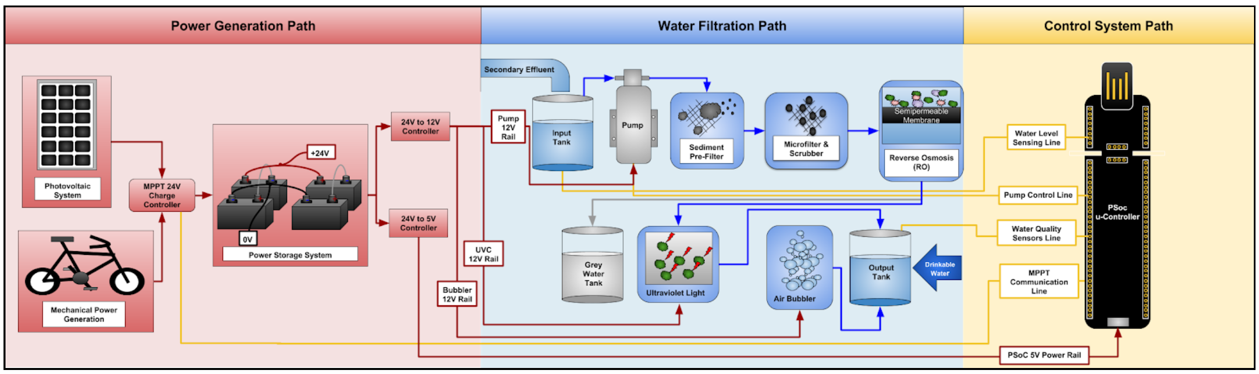

Figure 1. Three of the four essential subsystems and how they connect together in a broad sense. Each subsection is more thoroughly treated later in this document.

The Power Generation Path is controlled through the MPPT of the system, allowing for the batteries to be charged by solar and input mechanical power. The batteries then supply power to the pump and microcontroller. The water filtration path flows from a input source of water, a input tank is provided with the system, through three filtration stages, and finally through a Ultraviolet light component to the output tank. Tank water quality sensing, battery voltage sensing, and water level sensing is handled in the Control System path. The Control system path describes the autonomous control implemented in the waterlab system, allowing for simplicity. Each of these subsystems work in harmony to create a reliable and easy to use water purification system.

The last of the essential subsystems pertains to the physical structure of Waterlab, which we explain further under the “Body Design” section of this document. This section contains the physical frame that components are attached to, and supported by, as well as the means by which water is stored, sampled, and transported. To avoid redundancy, refer to the body section of this document for a detailed CAD model of the Waterlab Frame, as well as a fluid circuit diagram describing the water flow through the system.

Filtration System

The hydromechanical subsystem consists of the piping, valves, and intermittent components needed for safe filtration. **Figure 2** demonstrates the overall fluid circuit diagram[9] that has been implemented.

[9] Reference diagram components at: https://www.valmet.com/media/articles/up-and-running/reliability/FRFluidDwgs1/

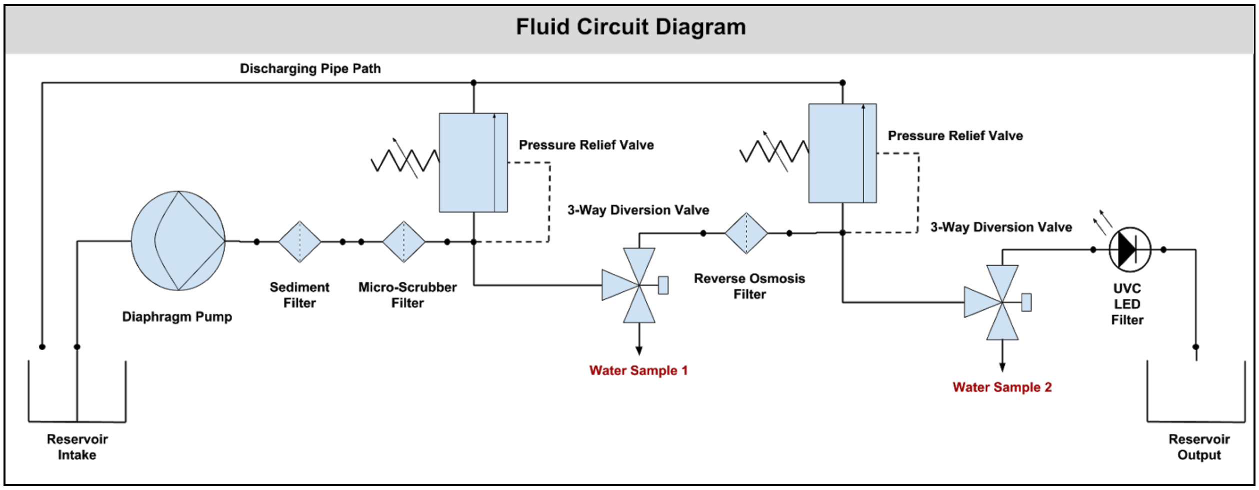

Figure 2. This Diagram illustrates the flow of water from input tank to output tank. Water samples can be taken in the intermittent stages for water quality testing using diversion valves, while the pressure relief valves provide a failsafe to protect filters and tubing from overpressure.

This fluid circuit diagram lays out the general pathways water can take in the system from the input tank.

The system layout in Figure 2 was tweaked from previous designs in order to increase efficiency, and decrease maintenance through the removal of intermittent tanks, and inclusion of two different valve types. Previous teams implemented a multi-pump system that would allow water to be filtered in stages and stored in intermediary holding tanks for the purpose of water testing. This design was deemed wasteful in terms of component replacements, inefficient use of space, and system weight. By implementing a single pump system with pressure relief valves and diversion valves,our design accomplishes the same goal of intermittent stage testing, while also reducing component maintenance, and system complexity. The addition of diversion valves and pressure relief valves allow for a simpler design as well as reduced system maintenance.

Waterlab is designed for modularity, meaning that the holding tanks, and input source are highly customizable for various applications. The operating specifications of the water pump was carefully considered for flow rate, pressure, and head. The head of a pump is the vertical pumping distance allowed, which is rated for one hundred and thirty-eight feet for the pump we chose. This means that our system can transport water a good distance to customized holding tanks. The tubing of Waterlab is made of polyethylene and is rated for a maximum pressure of eighty PSI. This tubing was chosen for flexible system setup and input/output setups. We inherited this tubing from previous teams, and decided to continue with it due to its convenience. The tubing design, and pump strength allows for waterlab to be used in customized systems, making it easier to use and install.

The pressure relief valves are a key component in the hydromechanical system due to the pressure ratings of the implemented pump. Any system that has pressure sensitive components, such as our reverse osmosis filter membrane, needs to have pressure relief valves that can mitigate damage to system components during moments of high pressure [Requirement WL-013 and WL-014]. Several relief valves were inserted prior to each diversion valve, for the purpose of avoiding spikes in pressures during diversion valve position changes. Spiking pressures can lead to pump damage, piping failure, as well as component damage. The implementing of the pressure relief valves allows Waterlab to be more robust, increasing the longevity of the system.

Filtration Process

WaterLab's filtration system incorporates several components from common household filtration. The filter process utilizes a pre-sediment filter to remove larger particulates, micro-sediment filter to remove smaller particulates, two semipermeable reverse osmosis membrane to remove smaller particles such as ions, and an ultraviolet light module to induce biological sterilization. **Figure 3** below shows a diagram for the different stages.

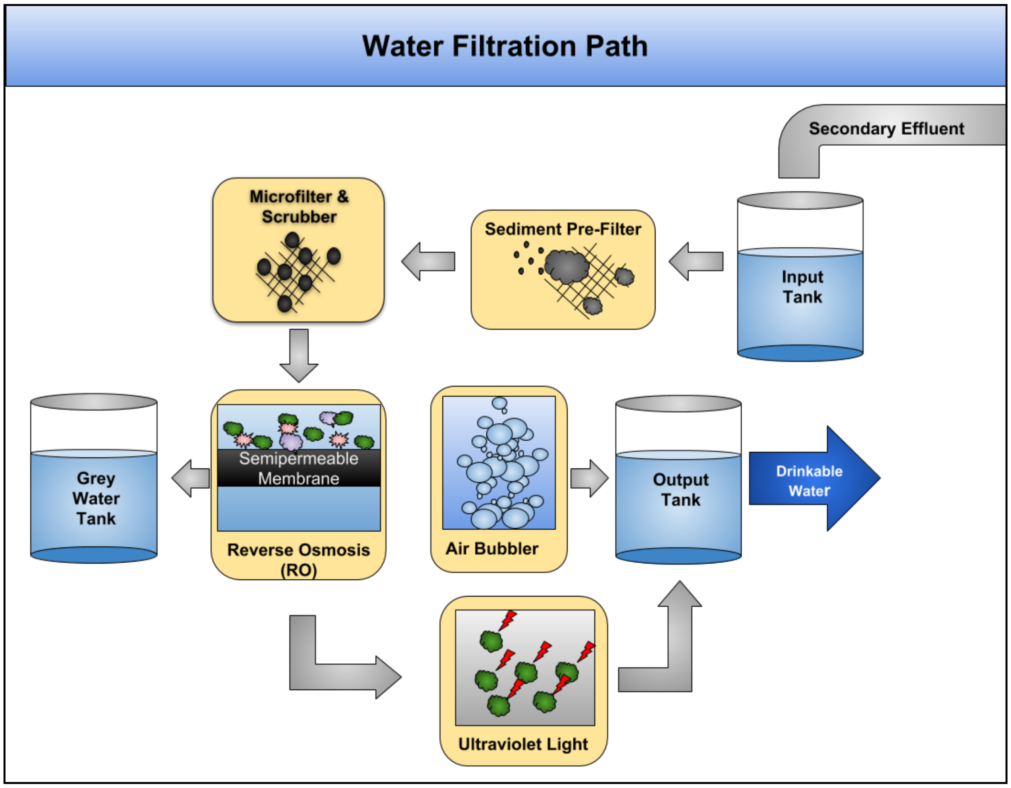

Figure 3. Block diagram of filter stages demonstrating the flow of the water into seperate filters

The WaterLab system implements a four stage filtration process. The primary filtration of solids is first accomplished by a standard housing filter. The water then goes through a micro-membrane sediment and charcoal pre-filter to ensure the water has become clear of chlorine which can damage the RO filter. The secondary filtration of water is achieved by using a reverse osmosis primary filter with a 1.25:1 waste to output ratio. The water is finally purified by the use of a UV filter. All of these filters combined clean and purify the water to give its users potable water at the output tank. The clean water output of the system is 26 GPH.

Pre-sediment Filter

This filter has flow rates[10] that far exceed the flow rate of the system, meaning that it will not interfere with the pressure requirements of the Reverse osmosis. This filter was chosen by the previous team, and proves to have no impact on system pressure to to high throughput ratings, while at the same time reducing the need for frequent replacement of the RO sediment filter, which is harder to replace. The flow rate of the filter is dated for four gallons per minute, which exceeds the flow rate of the system by more than three gallons per minute.

The pre sediment filter is rated to filter out the majority of remaining grit and sediment coming in through the input holding tank. The carbon core paired with a rated filtration of half a micron, this filter will remove the majority of grit and volatile organic compounds (VOCs) from the water coming in. Because the filter takes the brunt of the VOCs and grit, it will be the most frequently replaced filter fo the system

[10] For filter replacement and specifications see https://www.filtersfast.com/Pentek-CBC-20BB-water-filters.asp

Sediment and Charcoal Filter

To ensure water quality, filtration redundancies were implemented in the Waterlab system. The previous years followed this same mentality, but the secondary prefilter they chose ended up limiting the pressure and flow rate for the reverse osmosis. As a result, our team replaced the secondary prefilter with the Hydro Logic Tall Boy Filter[11]. The tallboy, like the first filter discussed, uses a a micro-membrane sediment and charcoal pre-filter. These filters remove suspended solids(such as bacteria, fats, and colloids) from the water. The redundancy of this filter removes up to 99% of chlorine and 90% of sediment from the water.

This secondary filter It is rated for two gallons per minute which means it will not limit the flow rate from the system pump that is rated for one point eight gallons per minute. It is important once again that a pressure drop does not occur in any of the pre filters since the reverse osmosis component requires a pressure of sixty PSI in order to operate at maximum efficiency. Ensuring a higher rated flow rate of the sediment filter allows for maximum water recovery of the reverse osmosis component chosen.

Reverse Osmosis Filter

A Reverse Osmosis Filter pushes water through a semipermeable membrane with the use of a high-pressure pump. This process requires a lot of pressure because it needs a certain amount of energy to reverse the natural process of osmosis (**Figure 4**).

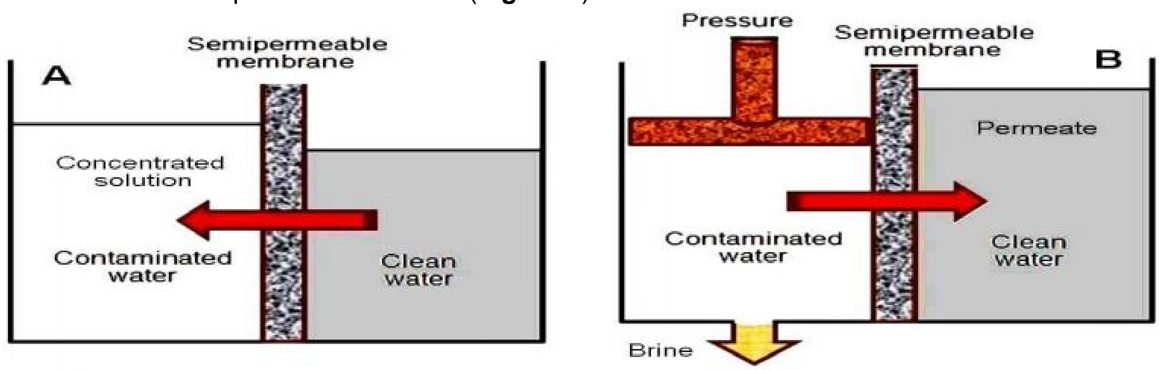

Figure 4: The basic processes of (A) osmosis and (B) reverse osmosis[12]

Reverse osmosis is a process that removes removes contaminants by an applied pressure producing a flow of wastewater while the clean water is passed through the semipermeable membrane. The efficiency of a reverse osmosis process is dependent on the applied pressure (between 40-80psi), concentration of solids, and temperature of the water. Unlike many other forms of filtration reverse osmosis is unique in its ability to remove salinity, heavy metals, and fluoride in addition to the removal of agrochemicals and toxins. Reverse osmosis is capable of removing 90-98 percent of the Total Dissolved Solids (TDS), 99 percent of the organics (including pyrogens), and 99 percent of all bacteria.[13]

Table 1: Contaminants removed by household reverse osmosis units.**[14]**

[11] Hydro Logic Tall Boy Filter
https://hydrobuilder.com/hydro-logic-tall-boy-de-chlorinator-and-sediment-filter-120gph.html?opts=eyJhdHRyaWJ1dGU0MjEiOiIyMTg2In0=

[12]Wimalawansa, S. J. Purification of Contaminated Water with Reverse Osmosis: Effective Solution of Providing Clean Water for Human Needs in Developing Countries. *Int. J. Emerging Technol. Adv. Eng.* **2013.** 3(12). 75-89

[13] Krishnan, S.; et al. Reverse osmosis plants for rural water treatment in Gujarat. **2007.**

[14]https://www.water-research.net/index.php/water-testing/private-well-testing/reverse-osmosis?fbclid=IwAR2PVdPjk-21SRgmh-cVHkdT9PW40TuzUgFBUq8nfr0ophPm1eRl94A2JS0

Ions and Metals	Arsenic, Aluminum, Barium, Cadmium, Calcium, Chloride, Chlorine$^{\Psi}$, Chromium, Copper, Fluoride, Iron, Lead, Magnesium, Manganese, Mercury, Nitrate, Potassium, Radium, Radon$^{\Psi}$, Selenium, Silver, Sodium, Sulfate, Zinc
Organic Chemicals	Benzene$^{\Psi}$, Carbon tetrachloride$^{\Psi}$, Dichlorobenzene$^{\Psi}$, Toluene$^{\Psi}$, Trichloroethylene$^{\Psi}$, Total Trihalomethanes (THM's)$^{\Psi}$
Particles	Asbestos, Protozoan cysts, Cryptosporidium
Pesticides	1,2,4-trichlorobenzene$^{\Psi}$, 2,4-D$^{\Psi}$, Atrazine$^{\Psi}$, Endrin, Heptachlor, Lindane, Pentachlorophenol
$^{\Psi}$ Activated carbon filters, commonly included in RO systems, can provide treatment for these contaminants.	

The Hydro Logic Evolution RO-1000 is the active reverse osmosis filter implemented in the system, and is the limiting factor for throughput of Waterlab's purification process. The filter's water flow is rated between 29 and 54 GPH depending on the input pressure. This filter requires pressure between 40 and 80 PSI to function efficiently and our current system gives an RO inlet pressure of approximately 54 PSI when operating. The functioning flow rate at this pressure is currently **60 GPH**, which is likely higher than the rated flow rate due to the prefiltering of the water before going into the RO. The currently tested active waste-to-clean water ratio produced by the RO is **1.25:1** ratio. The waste-to-clean ratio of the system is highly dependant on the system pressure ratings, and may improve or worsen depending on the contamination levels of the input water.

UV Filter

An Ultraviolet (UV) light filter is used as the final phase in purifying the water. UV light acts to deactivate microorganisms present in the water. This deactivation process works to make the bacteria unable to reproduce and therefore unable to cause infection.[15] UV filtration is an ideal form of purification

[15]https://www.prairiedusac.net/vertical/sites/%7B9B4AD25B-1470-4128-8A1E-0DB407531D87%7D/uploads/UVDisinfectionWaterApr10.pdf

because it does not introduce disinfecting chemicals, while being a low energy way of eliminating 99.99% of harmful bacteria.[16]

Water Testing

Collecting Samples

Previous years had implemented two inter-stage holding tanks that were hard to access and therefore deemed unfit for final prototyping. Instead of using several holding tanks, WaterLab implements water diversion valves between each filtration stage [Requirement WL-013]. This decision removes the need for having multi-stage pumps thereby reducing the power consumption of the system running at full throughput. Not only does implementing inter-stage diversion valves reduce the system power consumption, but it also greatly simplifies the maintenance of the water tanks as well as makes sampling from stages more convenient. **Figure 5** demonstrates the concept of implementing diversion valves.

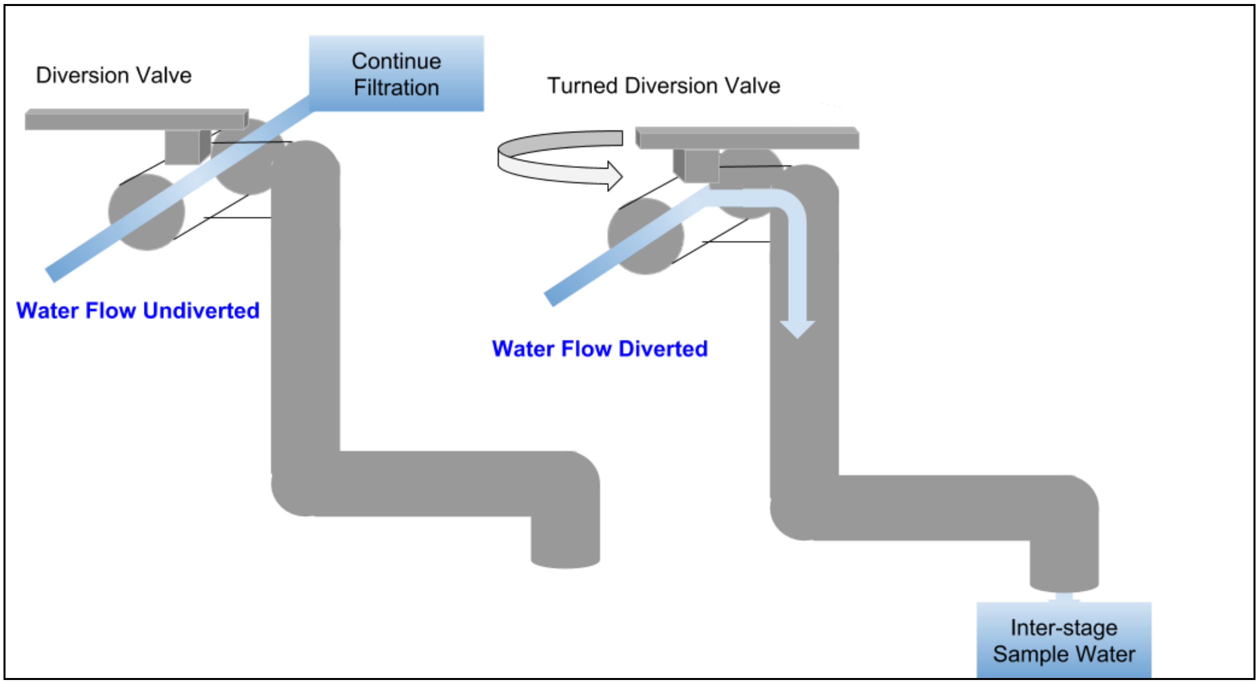

Figure 5. Diversion valve water flow through the system.

As seen in the figure, taking samples can be made by simply turning a handle to divert water from filtration.

Not all valves are created equally, which is why WaterLab implements ball diversion valves. These valves are more expensive, but have the added advantage of maintaining pressure, which is crucial for proper operation of the Reverse Osmosis unit.

Testing of Samples

Water of different qualities was run through the system to test the concentrations of many ions, as well as other key properties of the water. Testing was performed on initial samples and samples acquired from the diversion valves in-between each form of filtration. The major properties of the water are

[16] https://www.freedrinkingwater.com/whole-house/water-filter-knowledge-base/how-does-ultraviolet-water-purification-work.htm

analyzed by a Hach Pocket Pro+ Multi 2 Tester. A Hach DR900 colorimeter was used for analysis of ion concentrations. The Coliscan MF was used to test for coliform colonies.
Table 2: All properties tested and their acceptable values for potable water

Property	Acceptable Level	Instrument for Testing
pH	6.5-8.5	Hach Pocket Pro+ Multi 2
TDS	500 ppm	Hach Pocket Pro+ Multi 2
Salinity	1000 ppm	Hach Pocket Pro+ Multi 2
Conductivity	1055 μS	Hach Pocket Pro+ Multi 2
Free Chlorine	.5 ppm	DR900
Total Chlorine	4 ppm	DR900
Chromium	0.1 ppm	DR900
Nitrite	1 ppm	DR900
Nitrate	10 ppm	DR900
Phosphate	0.025 ppm	DR900
Sulfate	250 ppm	DR900
Copper	1.3 ppm	DR900
Zinc	5 ppm	DR900
Fluoride	2 ppm	DR900
Manganese	0.05 ppm	DR900
Iron	0.3 ppm	DR900
Coliform	0	Coliscan

The system's ability to remove contaminants at their Maximum Contaminant Level (MCL) was tested by the creation of a solution containing the MCL concentrations for lead, copper, iron, and zinc. This solution was run through the system and tested at each step of filtration. The DR900 colorimeter does not provide a means for testing lead, so the removal of lead and confirmation of the results of the other ions will be analyzed by inductively coupled plasma mass spectrometry (ICP-MS). ICP-MS tests concentrations as low as part per quadrillion and therefore provides extremely accurate results.

To test the system's ability to remove E. coli, a standard solution of E. coli was prepared and run through the system.[17] These samples were then tested by the Coliscan MF and the Quanti-Tray Sealer to confirm the amount of E. coli present between each filtration.

[17]https://cite.mit.edu/system/files/reports/Household%20Water%20Filter%20Evaluation%20%E2%80%94%20Suitability%20Consumer%20Reports.pdf?fbclid=IwAR1G1aoHNTR4UctAF9bJ5r9bxfyErSF8VJXKS9UmcRuBlsYLoamIGxqBjyM

Control System

System Goals

Our main goal with the control system was to minimize the amount of user responsibilities while maximizing the filter efficiency. The system will also contain an integrated LCD user interface prioritizing ease of use while maintaining comprehensive diagnostic data menus. The system will also feature various sensors and hardware modules to allow real-time detection and reaction to errors [Requirement WL-012]. Lastly, the control system will be well documented, implemented in an organized manner, and modular in order to allow the easy addition of new features. In order for the filtration portion of Waterlab to exist and help communities in need, the control system must work effectively and reliably. In order for communities to use the device themselves, the user interface must be easy to operate and responsive for the user.

Hardware Component Overview

Most of the hardware used in our system was inherited from the previous Waterlab teams because the parts were readily available, did not decrease our finite budget, and satisfied proper control functionality. Because our goal was to implement a working prototype, hardware research for maximizing system efficiency was not prioritized.

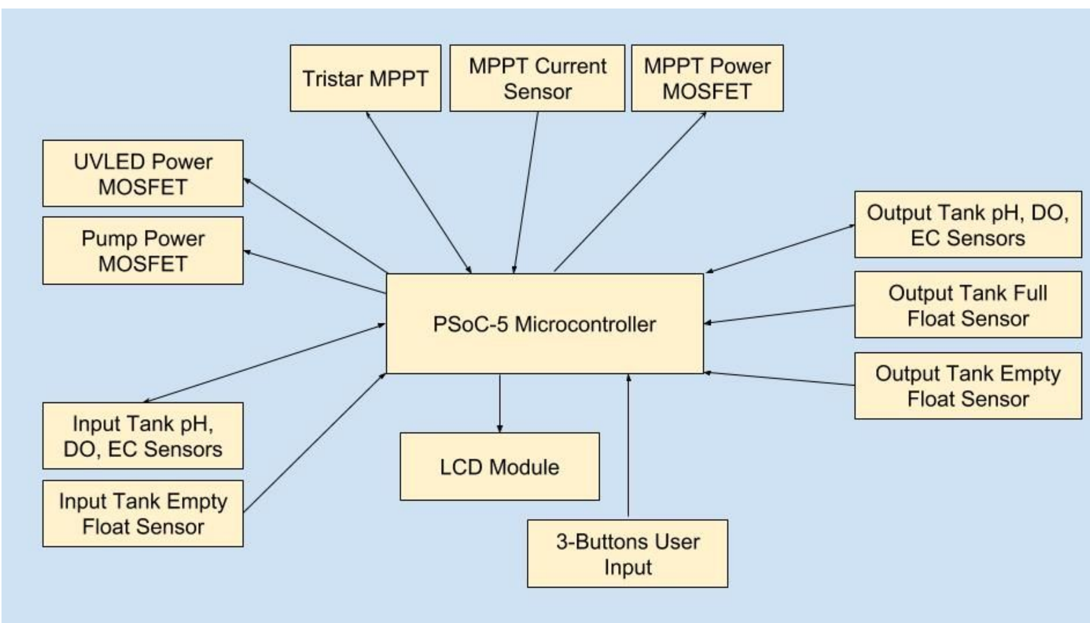

Figure 6. Control system hardware block diagram.

Microcontroller

Our system is driven by the *Cypress PSoC-5 CY8C5888LTI-LP097* microcontroller which provides flexibility due to the vast amount of features it provides.

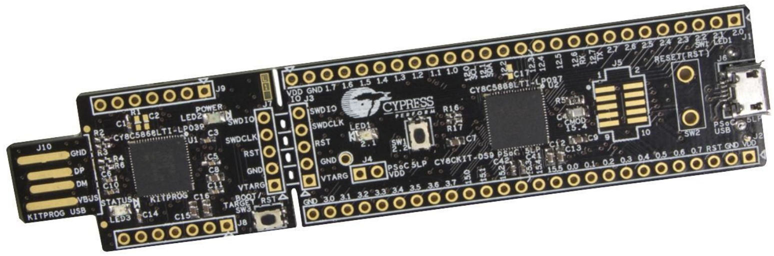

Figure 7. The PSoC-5 LP097 microcontroller is shown with its Micro-USB connection on the right, 38 GPIO pins on the top and bottom of the device, and USB programming port on the left.

The PSoC-5 (Programmable System on Chip) is a low power-consuming 5V microcontroller featuring 38 (General Purpose Input Output) GPIO pins. The system features digital and analog signal parsing and generation, various communication protocols, low power modes, and many other powerful features that can be found on the Cypress website[18].

Our team chose this microcontroller mainly due to the device's convenience. The device boasts many features which has allowed our implementation of new features to not be confined by hardware limitations. Also, we inherited many units of this device because it was the microcontroller choice of the previous two Waterlab teams so it was readily available and allowed us to not touch our finite budget.

Ultimately, this microcontroller is a good choice for our project's direction to produce a working prototype because of the microcontroller has many features and low power consumption. If our team was looking to optimize a more efficient microcontroller choice, we could look for a less powerful unit with less features and pins.This would then save some power consumption of our system although it would be extremely marginal.

Sensors

Our control system utilizes multiple *Annadson TRTAZI11A* water-level float switches to determine the water level for our input and output tanks. **Figure 8** shows the physical and circuit model of this component.

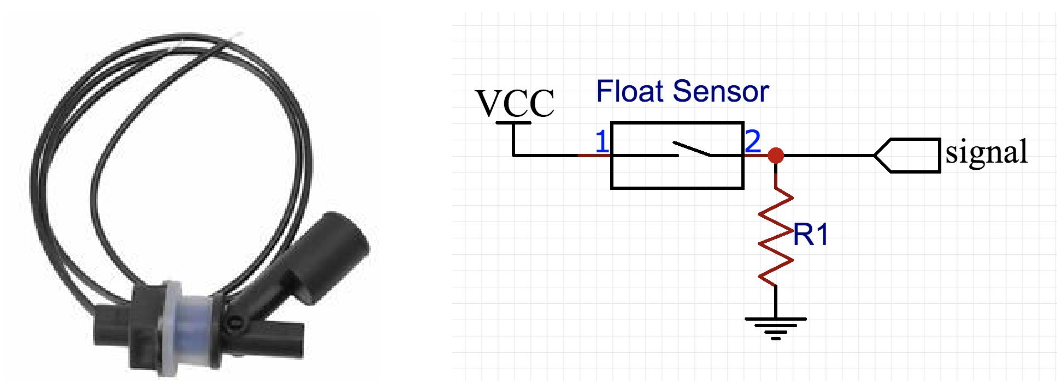

Figure 8. The Annadson water-level float sensor shown on the left and a pull-down resistor circuit implementation on the right.

Our team inherited many of these float switches from the previous WaterLab teams and the sensors were all in working condition. We found no need to research for a more efficient module.

[18] https://www.cypress.com/part/cy8c5888lti-lp097

When these sensors are connected in conjunction with a pull-down resistor they function exactly like an electronic switch in which the output signal voltage is either VCC when the switch is closed or GND when the switch is open. This signal is a digital signal which allows the microcontroller to read values from the sensor quickly by reading a *1* or *0.*

An important group of sensors our system uses are the *Atlas Scientific EZO* circuit sensors. Each of these sensors require an *Atlas Scientific Basic EZO Inline Voltage Isolator* in between the microcontroller connection and require Atlas Scientific probes specific to the sensor for the type of input to each circuit. Our system currently uses the *EZO Electrical Conductivity Circuit* with a complimentary *Atlas Scientific Conductivity Probe K 0.1, EZO Dissolved Oxygen Circuit* with a complimentary *Atlas Scientific Dissolved Oxygen Probe,* and *pH* Circuit with a complementary *Atlas Scientific pH Probe* in order to provide the user explicit feedback for water quality.

When connecting these sensors to our microcontroller, it is required that each sensor circuit is allotted two IO pins and a ground and voltage source connection: summing to four connections total. When using UART communication for the sensor, the module Rx and Tx pins are connected to the reciprocal microcontroller UART Rx and Tx pins. Then, the voltage isolator circuit serves as a middleman between the microcontroller and sensor circuit to guarantee no voltage interference due to the power sensitivity of the module. **Figure 9** below shows the wiring diagram of a pH sensor configuration.

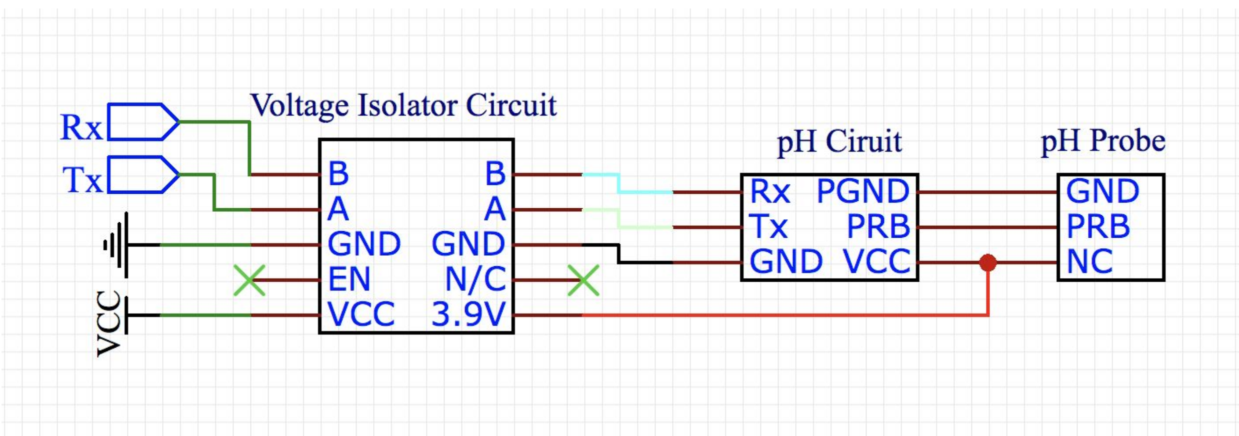

Figure 9. The pH sensor configuration for a microcontroller connection. The probe module is featured on the right and the connections on the left feed into the reciprocal microcontroller UART pins.

Each of these sensor circuits use UART or i2C communication protocols in order to send the sensors commands and receive responses. These circuits have 19 different commands including a calibration function, low power sleep function, read function, and others[19] which make them powerful sensor modules. Our team did not look into finding other modules since these components were already purchased by previous teams, and work well for the reading water quality. Conclusively, all components for these sensors were expensive but the sensors are well-made, and provide flexibility by having many useful commands.

There is a downside to these sensors, however, because they are suited for a lab environment. They require calibration every six months due to the sensitivity of the module and are fragile. Because we will deploy these sensors in both the detachable input and output tanks, protection and maintenance are crucial.

[19] The following link provides the datasheet for the *EZO pH Circuit* which has the same commands as the other *Atlass Scientific Sensors*:
https://www.atlas-scientific.com/_files/_datasheets/_circuit/pH_EZO_datasheet.pdf

User Interface

Our team made significant effort to improve upon the user interface made by the previous team. The previous team created a user interface that utilized an 11 led panel with three switches for On/Off, low power, and drain functions. An important addition that our system made was through the addition of an LCD screen. This screen will allow the user to access detailed text information about system diagnostics and state as well as allow and access to system control through an interactive menu. The menu control will be navigated through three push buttons positioned below the LCD screen. This implemented user interface, will allow the user to access many features and as well as manipulate filter functions easily and effectively. The design and functionality was built for simplicity while not sacrificing the amount of functionality it provides. **Figure 10** shows the design concept for our system.

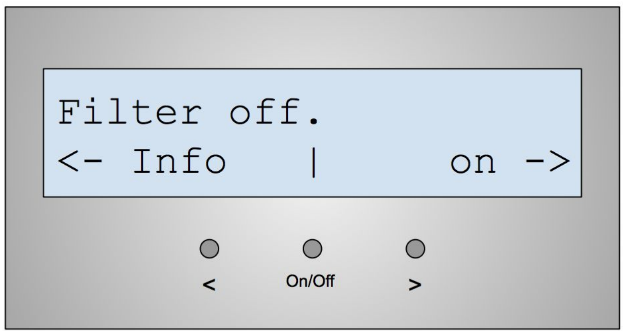

Figure 10. Three button LCD design concept with left, right, and On/Off buttons.

The LCD module that our team used was a low costing and simple 16 character, two-line screen named the *Adafruit GWT-C1627a v1.1.* This LCD module allows our system to display up to 32 characters of text at a time, upgrading our system to provide explicit and useful feedback for the user. We chose this LCD module because the PSoC-5 has a software library built in for this LCD which makes displaying text much easier compared to manually programming each pixel in the display. This LCD also features full RGB background coloring which we intend to utilize to indicate the severity of errors in the system. If the system requires the user to fix an error, the LCD can be driven with a red background. This color feedback adds an extra feedback technique to allow our system to communicate better with the user.

The datasheet and pin configuration for the LCD module can be found on the *Adafruit*[20] website.

When integrating the push buttons to be read by the microcontroller, our system uses a pull down resistor to make each push button a readable digital signal. The wiring configuration for the buttons are the same as our float sensor sensors. Both devices act as electronic switches and require a pull down resistor. The circuit diagram can be seen in **Figure 11** below.

[20] https://cdn-shop.adafruit.com/product-files/399/399+spec+sheet.pdf

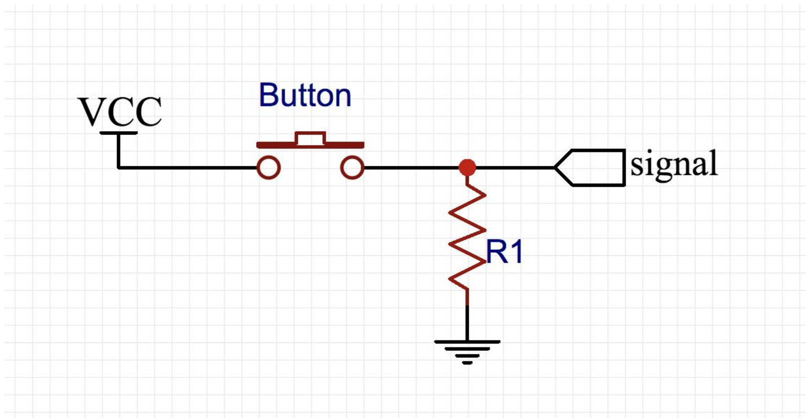

Figure 11. The pull-down resistor circuit shown for a digital button.

We configured each of the three user interface buttons to a unique microcontroller IO pin, and tied a hardware falling edge triggered interrupt in order to denote that the button had been clicked. Using a falling edge interrupt is the most logical interrupt because it will trigger once for every button press and the interrupt will occur right when the click is finished.

Our system could have used a rising edge interrupt or a level triggered interrupt, but these carry more disadvantages. The rising edge interrupt is slightly less ideal because if the client hold down the button the system will parse the signal when the button was first pressed down, which is not as natural as waiting for the entire click. A level triggered interrupt is not ideal since this interrupt would fire many time, since the 80 MHz clock speed of the microcontroller will sense the button is pressed down much more than once. This would force the software side to handle making the multiple signals a single event.

Power Control

Most microcontrollers like the PSoC-5 are low powered pieces of hardware. In order to drive high powered modules like our system pump, an external power source needs to be used. By using a MOSFET between the high powered module (pump) and power source (battery), a microcontroller can then send a voltage threshold signal to the MOSFET gate, which allows the high powered module to receive power.

A MOSFET is a transistor that is used to switch electronic signals. The MOSFET used by our system is n-type and its component name is the *STN4NF03L*[21]. This MOSFET is used for the purpose of power control, and acts as a current control device. When driving this module with a digital low signal of 0V, the MOSFET has a resistance so high that it acts as an open circuit, disallowing any current to run through the wire. When driving the module with a digital high signal of 5V, the resistance drops making it act as a short. **Figure 12** shows the wiring diagram for our implementation of MOSFET power control.

[21] Datasheet for the module can be here: https://www.st.com/resource/en/datasheet/stn4nf03l.pdf.

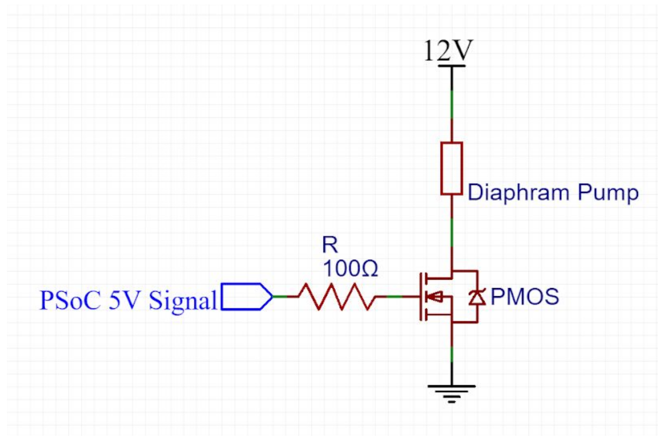

Figure 12. Power control using a n-type MOSFET.

Software Implementation

The PSoC-5 was programmed in C using the Cypress IDE named *PSoC Creator*. This IDE can be downloaded from the Cypress website.[22] The IDE features both coding and graphical portions to program the microcontroller, making it easier to use and implement new modules. The code is compiled into bytecode for the microcontroller and the graphical interface is utilized by the PSoC FPGA (Field Programmable Gate Array) capability.

General State Machine

When programming an embedded system, the software will continue to run while the microcontroller is powered on. This is handled by using an infinite loop with a state machine to control system functions. Once the system enters the infinite loop, system inputs determine the transitions to other states. **Figure 13** shows the overall flow diagram for our control system. On the left, the main method of the program containing the system state machine is shown and on the right the hardware triggered interrupt routines are shown. Although the system accesses more hardware modules for input, these four interrupt routines were needed to be handled by interrupts due to the speed of the signals. The system would not be able to catch these signals accurately through periodic polling.[23]

[22] https://www.cypress.com/products/psoc-creator-integrated-design-environment-ide
[23] A brute force technique to acquire a hardware signal in software by continuously reading the signal state.

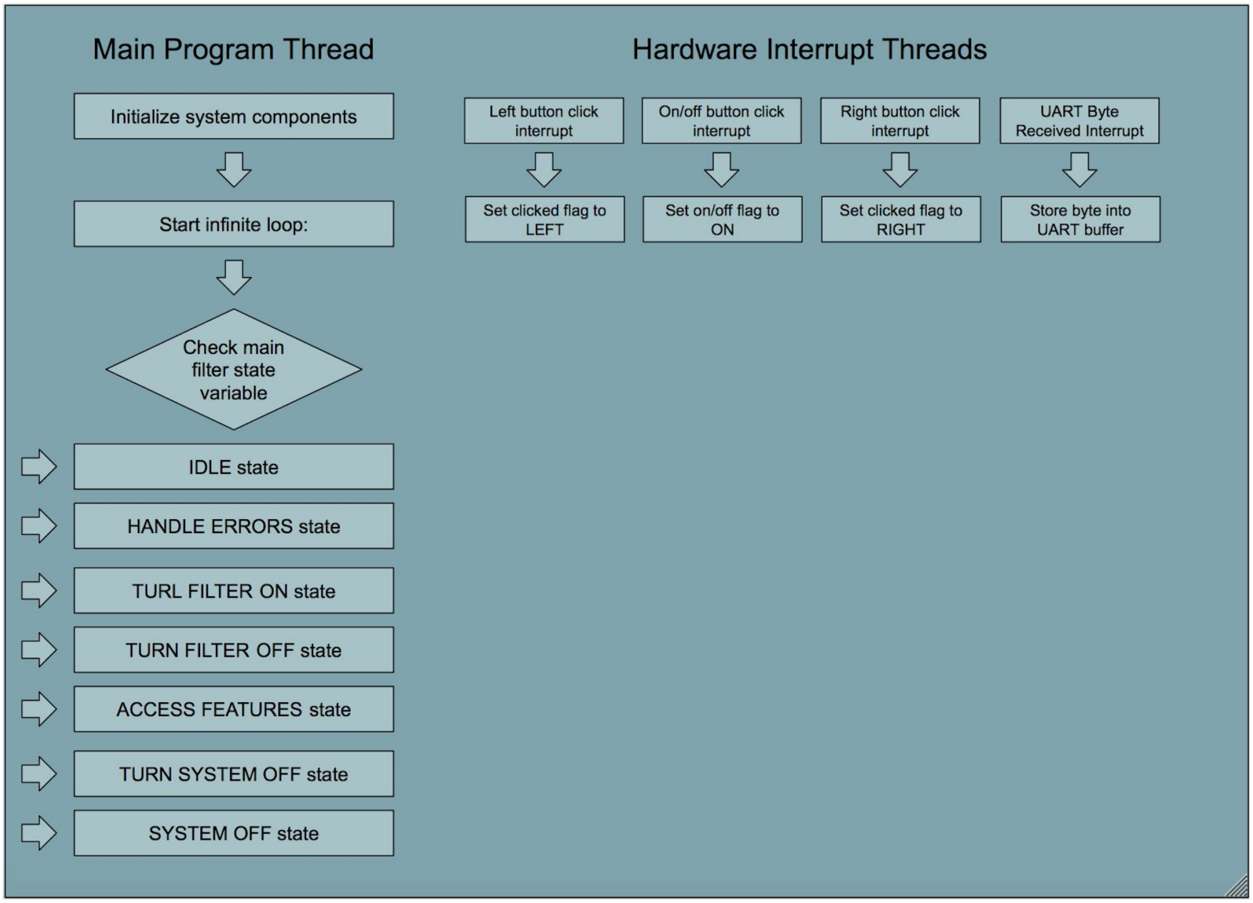

Figure 13. Basic flow diagram for the WaterLab 3.0 system.

Detailed Description of State Machine

When implementing software to control an embedded system the software will follow a general pattern:

1. On power-up, initialize all internal components.
2. Enter infinite loop and follow state machine.

Our control system is broken down by the following states: *IDLE, HANDLE ERRORS, TURN FILTER ON, TURN FILTER OFF, ACCESS FEATURES, TURN SYSTEM OFF, and SYSTEM OFF.* **Figure 14** shows a more detailed flow diagram of the main state machine along with its sub-state functionality.

The ***IDLE*** state is one of the most used states that the filter uses. This state first displays to the LCD the prompt for the state and whether the filter is on or off. It then checks for fatal errors that need to be resolved before the system continues functioning. If fatal errors were found it transitions into *HANDLE ERRORS* state. Then the filter checks for filter errors if the filter is on.

The ***HANDLE ERRORS*** state enters its own infinite loop where it can only break out of the loop after all fatal errors have been resolved. The system currently has three fatal errors: system battery is critically low, the input tank has been disconnected, and the output tank has been disconnected. Once the errors have been resolved the system goes back to the *IDLE* state.

The ***TURN FILTER ON*** state first checks the system if it is already on then it checks for filter errors that would disallow turning on the filter. If the system passes these two checks then it turns the pump on. This state always returns to *IDLE.*

The ***TURN FILTER OFF*** state doesn't need to check for errors because turning the system off will always be a safe operation. This state always returns to *IDLE.*

The ***ACCESS FEATURES*** state sends the system into an infinite loop that allows the user to access specific sensor data. This loop constantly checks for fatal errors and filter errors, in which once an error is encountered the system will return to the IDLE state.

The ***TURN FILTER OFF*** state turns all hardware components into low power and sleep modes in order to consume the least amount of power as possible. This state prepares the system for the transition into the *SYSTEM OFF* state.

The ***SYSTEM OFF*** state then maintains the system with all components turned off except for the interrupt tied to the on/off button on the user interface. Once the user presses this button, this state turns all components back and returns to the *IDLE* state.

The figure below shows a more detailed flow diagram of the main state machine and its sub-state functionality.

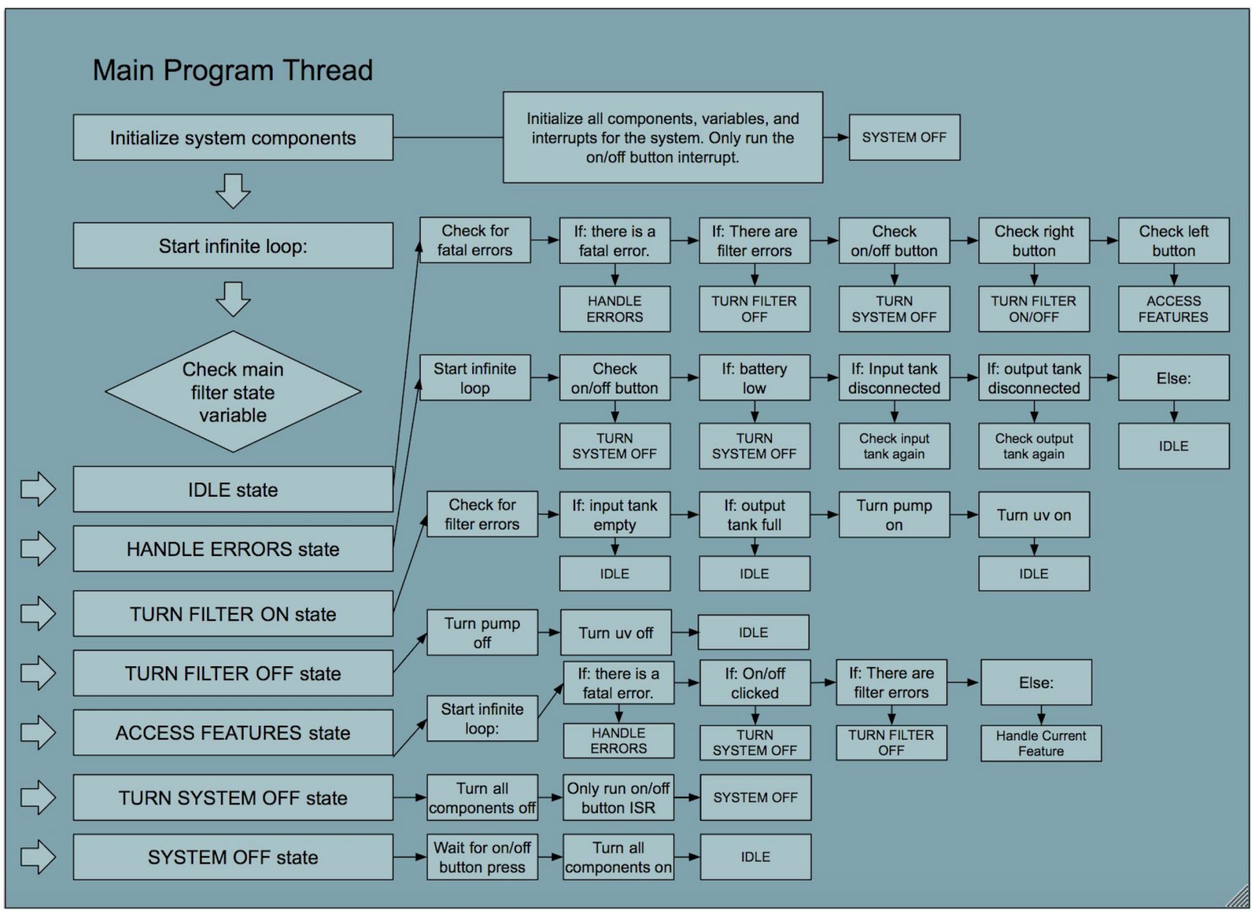

Figure 14. Detailed flow diagram for the WaterLab 3.0 system.

The ***IDLE*** state is one of the most used states that the filter uses. This state first displays to the LCD the prompt for the state and whether the filter is on or off. It then checks for fatal errors that need to be resolved before the system continues functioning. If fatal errors were found it transitions into *HANDLE ERRORS* state. Then the filter checks for filter errors if the filter is on.

The ***HANDLE ERRORS*** state enters its own infinite loop where it can only break out of the loop after all fatal errors have been resolved. The system currently has three fatal errors: system battery is critically low (if the battery level drops below the threshold of 30% charge), the input tank has been disconnected, and the output tank has been disconnected. Once the errors have been resolved the system goes back to the *IDLE* state.

The ***TURN FILTER ON*** state first checks the system if it is already on then it checks for filter errors that would disallow turning on the filter. If the system passes these two checks then it turns the pump on. This state always returns to *IDLE.*

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The ***SYSTEM OFF*** state then maintains the system with all components turned off except for the interrupt tied to the on/off button on the user interface. Once the user presses this button, this state turns all components back and returns to the *IDLE* state.

Power System

The goal of the power system is to provide sufficient operation time to meet the daily throughput requirements of the filtration system for providing enough clean water for its users. Requirement WL-002 defines the need for consistent, reliable power production for our system to properly function off grid. Our system accomplishes this through the combination of photovoltaic solar panels, to generate the bulk of the needed energy, and a mechanical power generator for emergency power in case the solar array fails to meet its required production goals. The power system also uses large batteries t

Ideally, the system should not need this back up power at all, but a balance had to be found between cost and energy storage capacity. The power system will feature a battery bank to handle energy storage and allow operation when energy production is too low or not possible–such as at night or during stormy, cloudy periods. The mechanical power generation will require user input and energy expenditure which may not be ideal, but provide a way for the user to charge the system during zero power generation periods.

Power Production

For continuous filtration, WaterLab requires a constant 118 watts of power. The power system must be sized to produce and store up to nearly 2000 watt-hours of power for 15 hours of continuous operation [Requirement WL-009]. The solar and mechanical power are integrated through a control unit fed into a Maximum Power Point Tracking (MPPT) charge controller, and fed into the system's batteries.

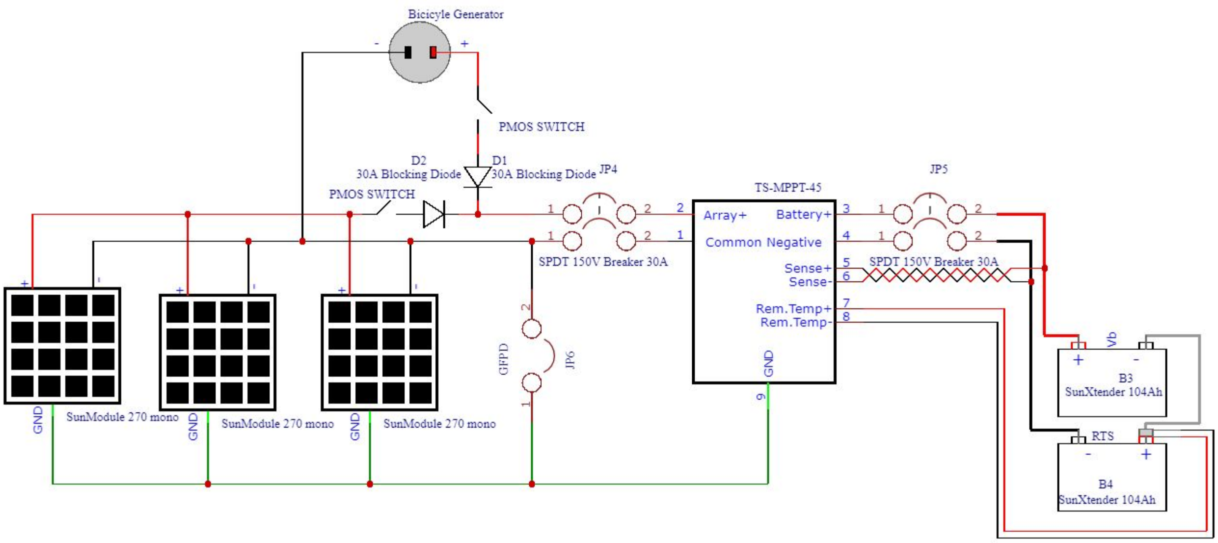


Figure 15: The power production and storage system shows the combination of solar and mechanical inputs to the charge controller along with the battery charging and sensor leads

Solar Power Production

Solar energy will be the main energy source for WaterLab system in off grid applications. The Sunmodule Plus SW 270 mono will produce up to two-hundred and seventy watts of power at full sun exposure. Our system uses three of these panels in parallel connection to produce approximately 31V and 25A at peak power, much more than the system requires for operation. WaterLab is designed this way to maximize its potential off-grid capabilities for variable deployment locations.

Figure 16. Pictured: SunModule Plus SW 270 mono[24]. This version includes 60 solar cells wired in series with a rated 39.4 V open circuit and 9.44 A short circuit. It will produce a maximum of 270W under the standard testing conditions at 25 ºC and 1000W/m^2. It features a box on the back where the positive and negative leads are attached with Amphenol H4 connectors.

We chose to use the solar panels in parallel due to their internal wiring. The solar cells within the panel are all wired in series, if current flow through one panel is prevented (by blocking the light, removing

[24] Solar World SunModule Plus SW 270 mono datasheet. http://www.siliconsolar.com/documents/datasheet-solarworld-270w-mono-solar-panel.pdf

the potential difference) the whole panel will not produce any current at all. This is an unfortunate characteristic of the solar panel which would cause a total loss of power if the three panels were combined into a series array. The material costs will be higher with parallel connected arrays due to the increase in necessary wire size, but the energy productions capabilities are far superior with our current set of solar panels.

The following report identifies historical climate patterns in Santa Cruz from a NASA's Prediction Of Worldwide Energy Resources: https://power.larc.nasa.gov/ This report serves as a guideline for all of the information used to calculate the expected solar power production for our system in certain areas. Useful information such as the proper orientation (N-S direction), angle of maximum irradiation, and typical daylight hours over certain periods of time are available for any location the user desires to operate WaterLab. Some of this information was used for deciding the proposed storage capacity and some is meant to be used by any persons setting up WaterLab in the field.

Solar Energy Transfer

The wiring from each solar panel will need to be combined into a parallel connection. This will require the use of screw terminals pictured below which are present inside of the breaker box.

Figure 17: The three 12 AWG wires from the individual solar panels will screw into their three respective terminals (Pos +, Neg -, GND). The larger 6 AWG wire will then run from the terminal, through a breaker and to the charge controller.

The wire gauge needs to be increased to be able to handle the necessary current according to NEC regulations. Our current design uses a PV combiner and breaker box to take in the wiring from each panel.

Figure 18. PV combiner/ breaker box setup for parallel PV array design. This setup is what the final design of WaterLab will use with 8 AWG Amphenol H4 connectors for positive, negative, and ground.

Safety Considerations

From the breaker panel, the wires will connect to the amphenol connections seen above. A separate set of wires will be used to run the length to the solar array. On the array side of the system, the positive and negative terminals will plug into each panel with H4 connectors as well. Note that these connectors are UL certified and completely waterproof with no added parts. They require a key to unlock which can be purchased from Amphenol on their website or from another distributor such as Amazon. There are similar connectors to the H4 such as the UTX or MC4 connections. The H4 and UTX type connections are fully mateable and made by the same distributor. Both of these options will work fine in these connections however the MC4 should not be used as a replacement. Last year's team chose to purchase a large quantity of MC4 connections to replace the more expensive H4 or UTX connectors however, these connectors are not rated to the same standards of UL certifications and are less reliable. The crimping connections are weaker and the pin headers are designed with less tolerance and therefore get stuck more often, risking damage to the solar panel connections.

When WaterLab is deployed in off-grid applications, the positioning of the solar panels will be the most important factor for determining whether the system is able to run as often as it needs to. The solar array harness should be long enough to be placed in the most ideal position under the sun, while WaterLab is more ideally placed in a shaded area. This would require nine connections to the array which could become a tripping or fire hazard if left separated. Accidentally tripping over these wires and breaking them would also cause damage to the charge controller and the solar panels. To prevent these issues, we will be using a conduit to contain the wires to reduce the potential hazards.

We chose to go with Liquidtight Flexible Non-metallic Conduit as it is the safest among all the flexible electrical conduits. LFNC is flexible, flame-resistant, water-resistant, and non-corrosive [Requirement WL-003]. As our system will be used outdoors and exposed to the elements, all of these characteristics will be necessary. It will also give the user the option to bury their conduit if they plan on maintaining the same set up for a long period of time and wish to avoid having the conduit above ground. [25] NEC NFPA 70 356.30(1) states:

> "Where installed in lengths exceeding 1.8 m (6 ft), the conduit shall be securely fastened at intervals not exceeding 900mm (3 ft) and within 300 mm (12 in.) on each side of every outlet box, junction box, cabinet,

[25] "4 Different Types of Flexible Conduits Explained," DoItYourself.com https://www.doityourself.com/stry/4-different-types-of-flexible-conduits-explained

or fitting. Where used, cable ties shall be listed as suitable for application, and for securing and supporting."[26]

The conduit for the solar array will be approximately 20 ft and therefore must be fastened. To comply with these regulations, the user must either bury the majority length (leaving no more than 3 ft of conduit exposed on either side), or securely stake the conduit into the ground.

Mechanical Power Production

The mechanical power production for the system was chosen to be a backup solution for time of prolonged low solar irradiance. Due to the large amount of power required to operate the system as well as the limited power capacity of the power storage system, a backup power solution was added to WaterLab's design. The mechanical power produced by the pedal power system will be regulated alongside the Solar power collected through the Tristar MPPT controller. Using current controlling and sensing, the pedal power will be able to be dynamically integrated as a charging source. The layout for this can be seen in **Figure 19**.

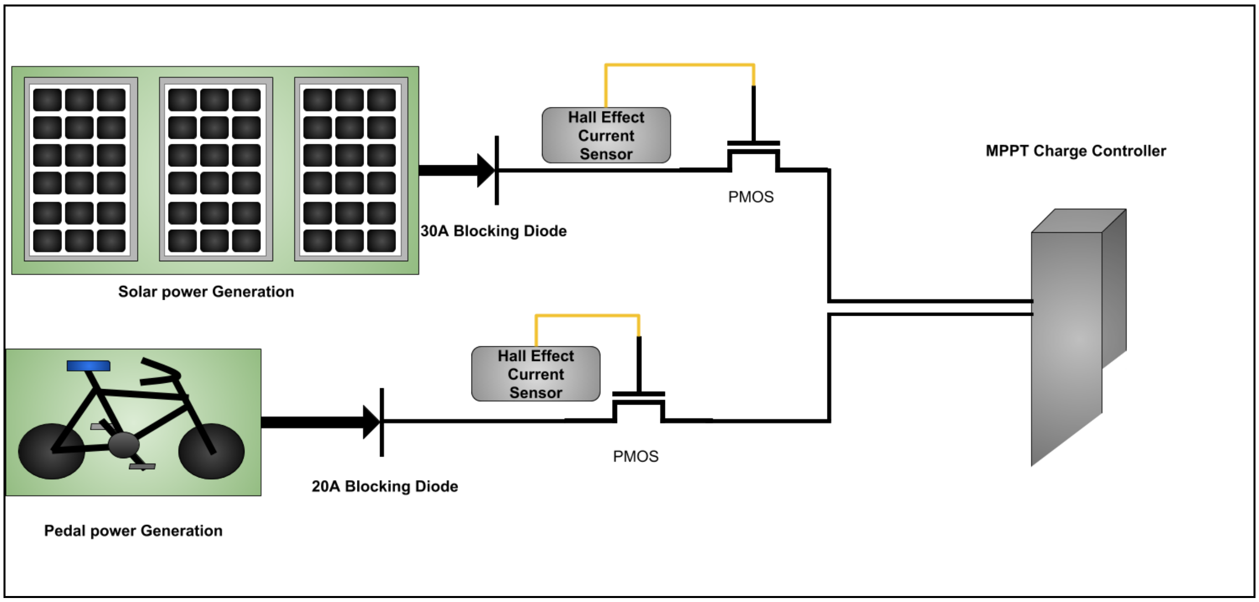
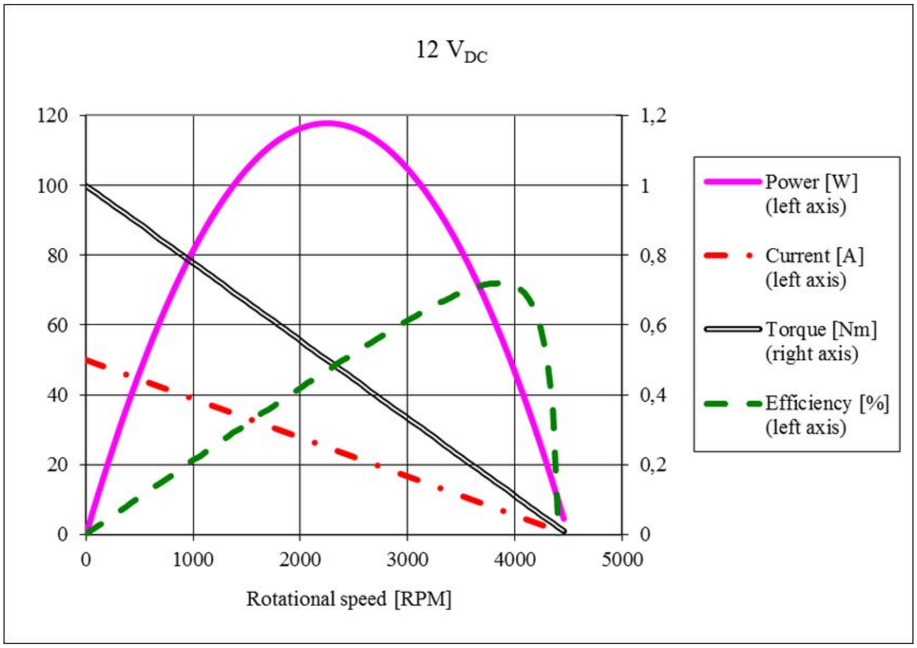


Figure 19. Power system diagram for power generation methods. The hall effect sensors will control the ability for current to flow to the MPPT through the use of a microcontroller in order to prevent overcurrent through th MPPT. Solar is the prefered current source for this system.

The power flow is controlled through PMOS devices by way of the microcontroller. If current is at a peak allowable value through the MPPT of 45 amps, then the PMOS will limit or shut off all current flow from the mechanical power generation, and display to the user to not attempt to pedal for additional power.

The mechanical power production component that was chosen is capable of producing up to three-hundred watts of power depending on the intensity of movement, and was the cheapest pre-build option on the market for the supplied power. The Pedal-A-watt pedal power generation component is a permanent magnet generator that is advertised to produces on average 300 watts. **Figure 20** below depicts a graph of power production that correlates to the rotational speed of the motor.

[26] NEC NFPA 70 2017 edition: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70



[27]

Figure 20. Power to RPM graph for the Pedal-A-watt system.

The Pedal-A-watt has a maximum capability of producing 15A at 65V, with a constant voltage level at rotational speeds of 1000 to 9000 RPM. As an approximation, a easy cadence (140 rpm --> 10 mph[28]) on a 24 inch bike wheel produces a rpm for a 2 inch diameter cog of (140 rpm * 24 in / 2 in) = 1680 rpm on the cog. Bikes are able to produce speeds up to 631 rpm (45 mph), so reaching the full 9000 rpm will not be possible (max 7572 rpm). From this we can assume the maximum power output of a 24 inch pedal is (15A * 65V)*(7572 rpm /9000 rpm) = 820.3 Watts MAX. Torque calculations will have to be performed to determine feasibility of these speeds at another time. We can expect that at the worst, the pedal-a-watt will produce an expected average of 182 Watts**.** This is more than the total power consumption of the system, meaning the system will be able to function from just this source if necessary. [Requirement WL-010]. A person that is in poor shape can still easily provide the power to run the system using the pedal-a-watt component.

The device comes with a 20A blocking diode which will not allow the current from the solar panels to turn the generator into a motor or restricting usage as a generator for the permanent magnet component. The blocking diode is an important component since any permanent magnet generator can become a motor with a reverse in current direction. We do not want to have any wasted power or dangerous conditions that would result from powering the generator as a motor unintentionally.

Power Conversion

The charge controller will ensure we obtain the most efficient battery charging for times when full sunlight hours are limited, such as in the winter when daytime is shorter and during intermittent storm cycles. We are developing this system for use in Santa Cruz, CA which allows us to design a robust system due to our low average sunlight hours.

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[27] This is the expected curve shape, taken from https://www.researchgate.net/figure/PM-brushed-DC-motor-characteristics-From-it-can-be-concluded-that-the-maximal-torque-of_fig13_269270635

[28] Rpm estimations source webpage: https://endless-sphere.com/forums/viewtopic.php?t=16114

Maximum Power Point Tracking

To maximize solar energy output, a MPPT device is implemented in our system with solar panel power input that reaches nearly maximum efficiency for the device. Our device chosen was MorningStar's 45A Tristar MPPT[29] which was inherited through previous years team purchases. Through our product comparison research, we discovered that MorningStar is one of the best companies on the market for their solar charge controllers and the TriStar is one of the most robust products they have. Last year's team made their purchase after determining that the 45A model would fit their needs just fine. Although it would otherwise have been possible for our team to increase the capacity of our system, it would not be totally necessary and we took this rating as one of our constraints. **Figure 21** shows the 24V efficiency graph for varying levels of input power to the MPPT.

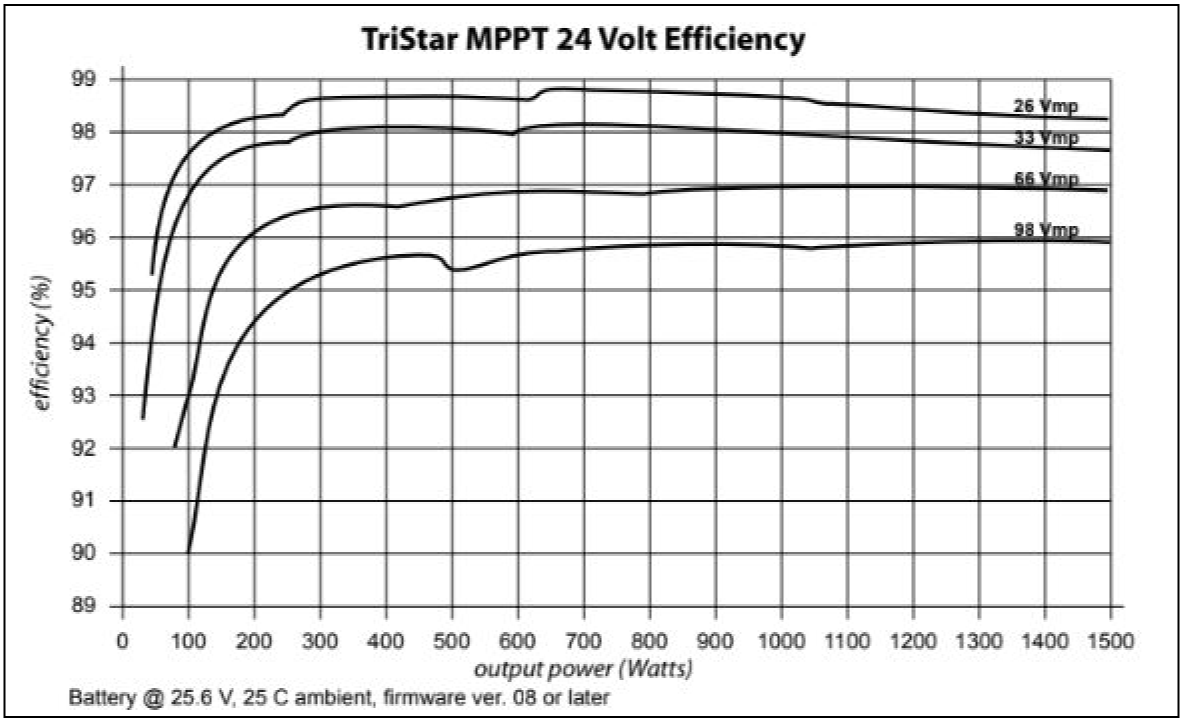

Figure 21. Tristar MPPT charging efficiency for a 24V system at varying power input.

From the graph, it can be seen that the maximum efficiency occurs near a input power of 800 watts. For this reason, we will be implementing the system as a 24V system with the three solar panels purchased that total to a maximum of 810 watts of power at datasheet testing conditions.

Voltage Regulation

Because our system runs at a nominal 24V, a DC to DC converter in needed to supply proper voltages to the 12V pumps and 5V microcontroller. Each of these devices has its own efficiency that was checked and included into our final power budget

[29] Tristar MPPT device manual source site: https://2n1s7w3qw84d2ysnx3ia2bct-wpengine.netdna-ssl.com/wp-content/uploads/2014/02/150V-TS-MPPT-Operators-Manual.pdf

The i6A4W Voltage Converter[30] is used in the system to step-down the 24VDC to 12VDC. It has a rated power efficiency of 97% for our conversion. This is a high power efficiency compared to other converters so that is why it has been chosen for this system. In our tests we experimentally found the power efficiency to be 96.5%. This was just an isolated test with one of our pumps and the converter where we put in 24VDC and 0.72A (P_{in} = 16.67W) into the converter and saw 11.99VDC and 1.39A (P_{out} = 17.28W) across the pump.

$$Eff = \frac{P_{output}}{P_{input}}\% = \frac{16.67W}{17.28W}\% = 96.5\%$$

Power Storage

Power storage is a critical factor for using photovoltaic systems. The challenge with implementing a filtration system that runs off of solar power is sizing the energy storage system to the needs of the device. Batteries are the only storage type used within WaterLab, and they have been sized according to the upper bounds of the design power requirements to allow for maximum power system longevity versus design cost.

Batteries

Absorbed Glass Mat (AGM) lead acid batteries proved to be the best option for energy storage for several reasons. Firstly, AGM batteries tend to have a larger range of allowable Depth of Discharge (DOD) than other lead acid or cadmium batteries. Having a larger allowable DOD in beneficial since more of the battery capacity can be used on a daily basis without damaging the chemistry of the lead acid battery. Secondly, AGM batteries, like other lead acid batteries, have a large voltage tolerance rage. This voltage tolerance allows for a battery to be less susceptible to thermal runaway, preventing hazardous fire situations that are common among lithium ion batteries. Lastly, AGM batteries provide a cheaper option than Lithium ion, while also having larger discharge currents than other lead acid batteries. Our system has a requirement of near nine amps of current to operate at full power, and therefore this high amperage rating puts large limitations on the battery types available for consideration.

Previous teams purchased AGM batteries by Sun Xtender. These batteries provide a nominal capacity of 104 AH at a voltage of 2V per cell over six cells -- or 12V. These batteries were a wise choice due to their discharge currents, and well documented user manual.[31] The only addition that needs to be made is the number of batteries. The sizing of batteries can be difficult task since it involves understanding charge currents, discharge currents, system load, and load duration. The previous years team did not account for discharge currents or duration, and therefore purchased two batteries less than what is needed for system operation. Our system implements four batteries in a series parallel formation as seen in **Figure 22**.

[30] i6A4W Voltage Converter https://www.digikey.com/product-detail/en/tdk-lambda-americas-inc/I6A4W020A033V-001-R/285-2503-ND/5878834

[31] The Sun Xtender users manual can be read on the site: https://www.solar-electric.com/lib/wind-sun/techmanual.pdf

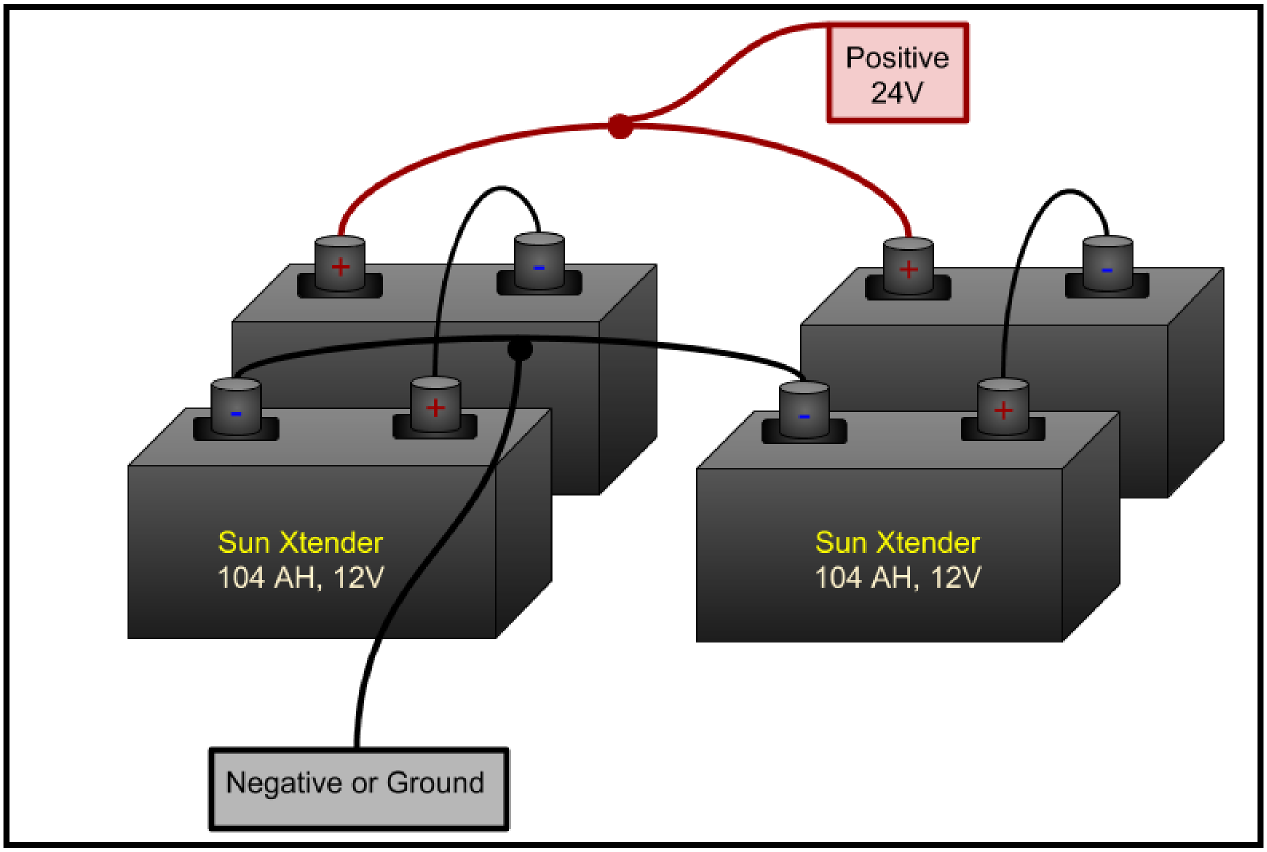

Figure 22. Parallel series connection for the WaterLab power system that allows for maximum expected charging currents, daily capacity, and discharge currents.

The resulting series and parallel combination connection will allow the system to charge and discharge without heating the battery as well as provide enough energy storage for fifteen hours of operation under a load of eighty watts without going below 30% DOD. If the system does not go below 30% DOD throughout its charge and discharge cycles, and is maintained at a temperature between 180F, it can be expected to last for one thousand eight-hundred charge cycles, equating to a little under five years.

The choice for 24V for our system comes from a combination of load current requirements, and charging currents from the MPPT. having a 48V system would lower charging currents, but limit the load currents, and having a 12V system will cause too high of charging currents through the MPPT -- rated for 45A. Having a 24V system with four batteries is the middle ground for keeping battery heat to a minimum during charging and discharging, as well as allowing for acceptable currents to flow through the 45 amp maximum of our MPPT device. Having a 48V system with two parallel stacks would be ideal for charging and discharging, but the cost, system weight, and maintenance would be too great of a burden to be worth implementing in our system.

Power Budget

The filtration system accounts for 90% of WaterLab's power consumption. This single biggest load is the water pump, which takes up over 70% of the energy budget for our project at a maximum power draw of 86.2 watts. During operation, the pump will draw power according to the pressure of the system. Our system will be set to operate between 60-80 psi and therefore draw approximately 7 amps of current.

The control system has several small electrical loads that we can consider. One group of loads come from the required sensors of the project. A second source of power is the microcontroller itself.

Lastly, we have the power draw of the user interface LCD LED Screen. The control system in total makes up less than 1% of the power consumption and is nearly negligible in terms of hours of operation.

Table 3. Power Budget

Component	Company	Description	Subsystem	Power Draw (W)
		Pump	Filtration	86.2 W
Pearlaqua Micro 9C	Aquisense	UV	Filtration	11
		Bubbler	Filtration	5.52
GWT-C1627a	Adafruit	LCD Screen	User Interface	0.1
PSoC5	Cypress	Microcontroller	Control	0.01
		pH Sensor	Control	0.0675
		eC Sensor	Control	0.0675
		DO Sensor	Control	0.0675
Total				118.06

Body Design

Solidworks Model

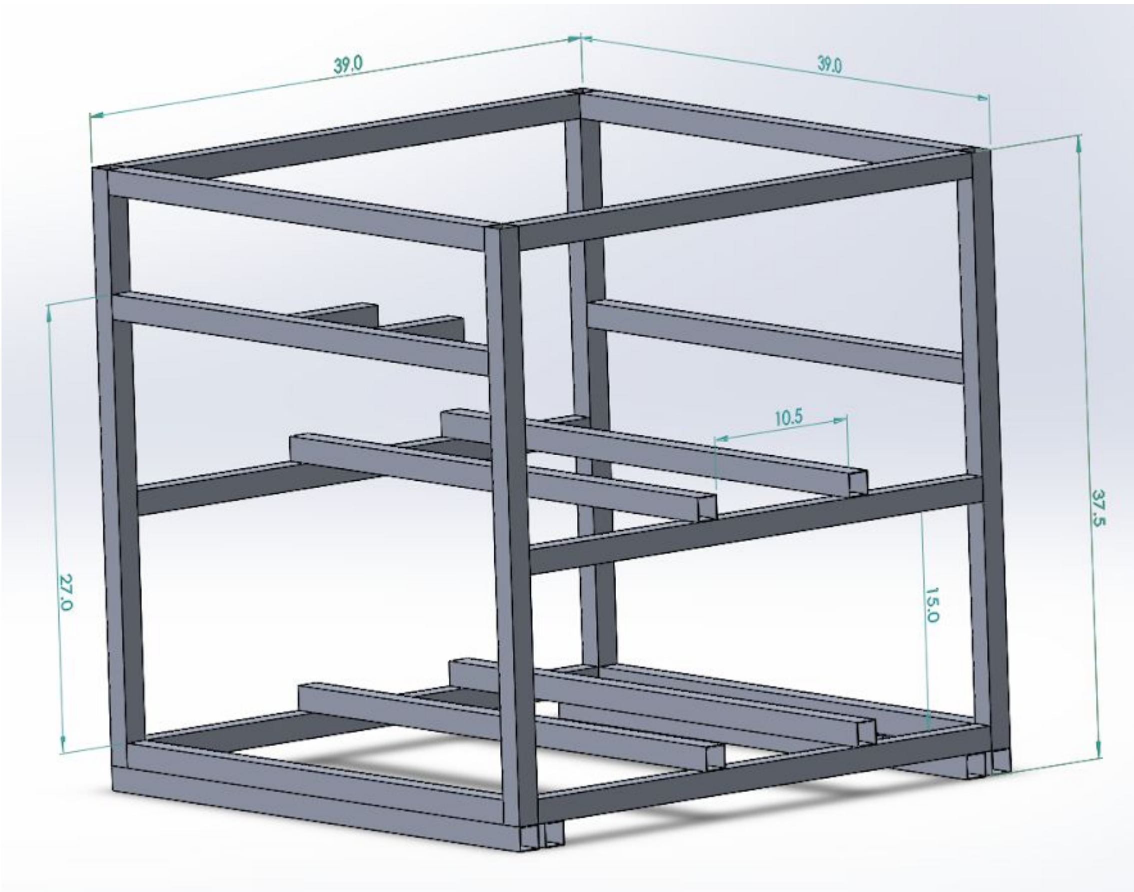

Figure 23. WaterLab Frame CAD Model

A robust, well-designed, frame was needed to support the heavy weight of the batteries and filters. **Figure 23** displays the SolidWorks CAD model with all of the components transparent. This model was created to plan out the construction of our frame. The frame is composed of square tubing with a height and width of 1.5”. In total this design uses sixteen 36” segments, eight 39” segments, and two 6” segments. We choose this size so it could be large enough to support all of our system components and be small enough to fit in the back of a short bed truck with a bed width of 4’ and length of 6’6” [Requirement WL-001]. The spacing of the system is based on the 3” spacing of perforations on the square tubing.

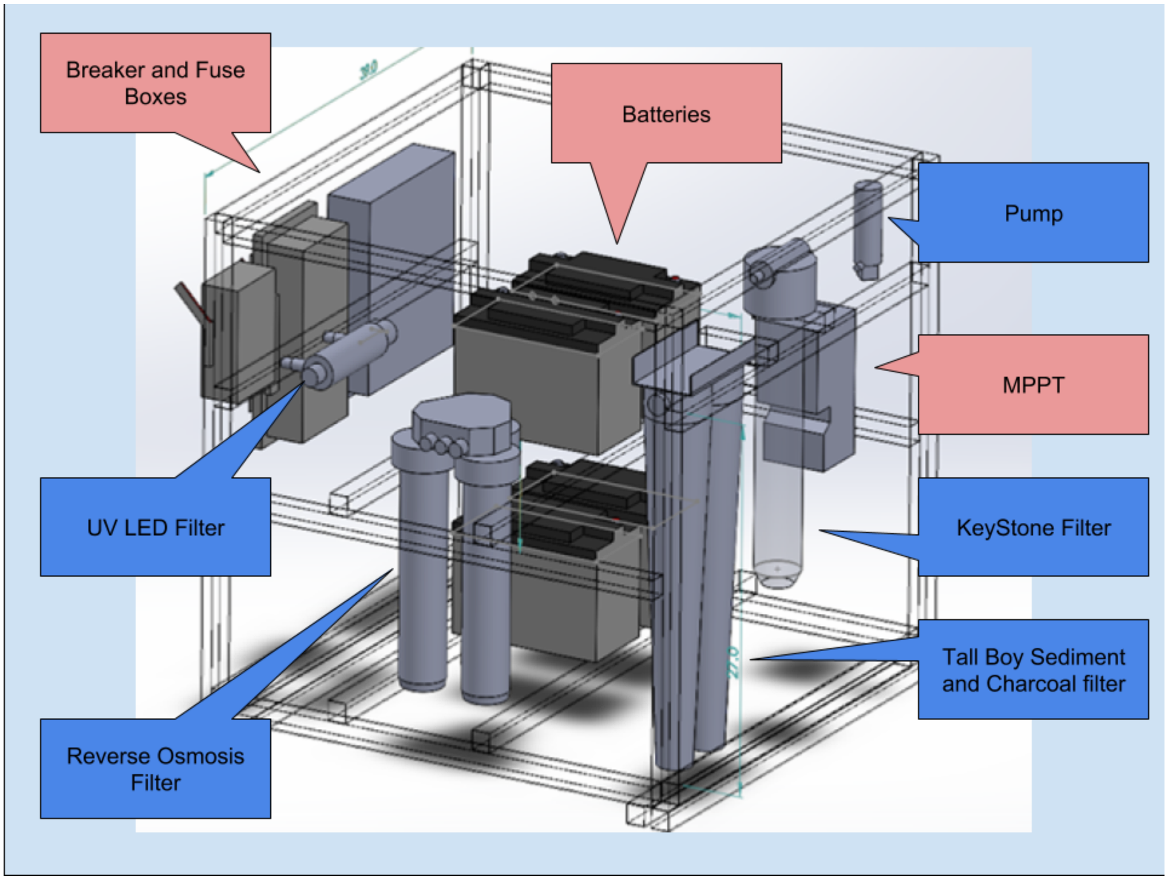

Figure 24. CAD Model System Component Spacing [Top View]

The components of the system had to be minimally spaced out to have a final system size capable of fitting in the back of a truck. In designing this frame the team also had to consider all aspects of the device. The MPPT generates a large amount of heat when in use. To ensure safety of the user and system from any damage we gave it at least 6" of clearance on all sides. The batteries for the system were placed on a shelf that does not touch the bottom panel of the system to protect them against potential puddling on the base of the system. All of the breaker and fuse boxes were placed onto one single side for user ease of access. Each one of the filters in the system will need to be replaced throughout the system's life. The system will implement the use of doors and an openable top panel to give the user easy access to the filters for replacements [Requirement WL-006]

Frame Components

To create the actual frame of the system we choose Aluminum Square Tubing[32] because it is half the weight of steel and is weather resistant [Requirement WL-001 and WL-003]. The square tubing used for the frame has perforations every 1.5" with a hole diameter of 0.328" (5/16"). This allowed for easy assembly and movement. Welding non-perforated aluminum square tubing would make the system sturdier, but our team decided against this because we wanted the option to move frame components in case of any design changes.

[32] Aluminum Bolt-Together Framing
https://www.mcmaster.com/8809t7

To mount all the components on the inside of the frame we used metal sheets that are 1/16” thick and lightweight. The metal sheets were cut and customized to fit the component mounted, and proved a sturdy support for each component. Having a sturdy support allows for ease of transportation, as well as a lower potential for component damage through dismounting. Implementing sheet metal was chosen for the maximum longevity of the system.

Outer Walls

The system will be outdoors for most of its use and transported from one area to the next. To protect the system we needed to implement durable and lightweight outer walls. Plastic [33]is both durable and lightweight so that is why it will be used as our outer protecting walls. The plastic will waterproof the device as well so the electronics do no get wet from any rain or flooding. The team will also be ensuring the system is waterproof by sealing any seems we have on the outside of the system. [Requirement WL-003]

The system also features a hinged top for accessing the components more easily on the inside. This top is insulated using a sealant around the edge to prevent any water from seeping in and has a latch to provide a way to keep the seal tightly secured during use or transportation. [Requirement WL-006]

Expenses and Budget

Requirement WL-004 states WaterLab **SHOULD** cost no more than $5000, an affordable long term option for water filtration. See Appendix C for a comprehensive breakdown of the total parts list of all the integrated components and breaks down the costs with part links. WaterLab is going to be used in small, distributed, off-grid application in areas that are not affluent enough for grid infrastructure and therefore need affordable options. Our total cost come out to $4,866.10 in parts for our currently implemented system. This number includes all of the parts purchased over the last three years that are in use for the system, but does not include any older parts that we will not be using. As a research project and proof of concept, WaterLab has incurred more costs, but the goal we are attaining with WL-004 is in relation to the material cost of solely the final product so reproducing the system is possible.

Funding

Funding Received

We received funding for WaterLab from the UCSC Carbon Fund, an initiative from the student body to fund carbon reducing and sustainability projects. Upon project creation in 2016, Carbon Fund granted the project $7000 for the general project budget. In 2017, WaterLab received another $700 for extra funds to purchase a low-power UV LED. From this amount, our team had $1400 left over. We applied for an additional grant in 2019 and received $1169. This supplied enough funds for the majority of our remaining needs but left us short from implementing the mechanical power generation circuit.

We applied for a second grant with Stevenson College Student Project Fund and received $500 for the purpose of building the mechanical power generation circuit.

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[33] The plastic used can be found at the following website https://www.lowes.com/pd/Parkland-Plastics-48-in-x-8-ft-Embossed-White-Matte-Plastic-Wall-Panel/3436816?cm_mmc=SCE_PLA-_-Millwork-_-InteriorWallPanels-_-3436816:Parkland_Plastics&CAWELAID=&kpid=3436816&CAGPSPN=pla&store_code=1756&k_clickID=go_625709507_34614230230_111133241110_pla-259590007610_c_9032158&gclid=EAIaIQobChMIk6SPsun33gIVXB6tBh3-tQJUEAQYAyABEgIT0vD_BwE

We receive additional assistance from the Sustainability Lab of UCSC which provides lab space and test equipment for us to use, in addition to a minor amount of materials such as wiring for soldering and prototyping. S-Lab has also provided the Trojan J200 batteries for use during our prototyping and proof of concept phase.

Funding Remaining

We have approximately $600 left in our budget for implementing the mechanical power generation and purchasing the required upgrades to the power system to meet NEC requirements.

Future Funding Opportunities

There are many grants available in the future that WaterLab can apply to. The Stevenson and other college grants are available every quarter here at UCSC for student-led projects and the Carbon Fund application is available every year in the fall. Giving Day at UCSC is another option with the ability to be a very successful crowdsourcing opportunity with proper advertising. WaterLab 3 does not plan on raising any more funds for the 2018-2019 school year, but future teams can always apply for the same funds if they require more funds to fulfil their budget to finish any future work.

Further Work

Final Product Material Preferences

Some of our chosen materials in use in our prototype design, do not match our preferences for a final product. This is on purpose in some circumstances so that we could produce a more inexpensive proof of concept and because long term (constant use) capabilities were not an immediate concern. For example, certain material use in the water flow system can be affect by imbalances in the pH or minerals in non-potable water, which could cause these materials to degrade (eg. certain plastics, zinc, aluminum, copper, brass, etc).

Control System and Sensors

The current control system is robust and simple to use for a non-expert user. Educated or expert users may wish to have more diagnostic information displayed to them and have more control over the functionality of the system. If this is the case, the control system code is built with the capability to alter control format and display the diagnostics of every sensor. It also allows for more sensor integration.

The PSoC5 microcontroller has 38 I/O pins and can handle much more sensor integration. WaterLab currently uses 3 water quality sensor in the output tank for quality verification and validation. Ideally, WaterLab will use the same water sensors in the input tank as well to verify the changes in quality that WaterLab achieves.

Power System and Batteries

WaterLab bases its needs off of the need for a 4-person family using the system to achieve its requirements for water throughput and therefor power needs. If these change at all, the values will have to be adjusted. In addition, battery maintenance is a very important aspect to keeping the system life as high as possible. The SunXtender and Trojan batteries we inherited from the years passed were not tended to and have largely lost their normal lifespan. New batteries may possibly need to be purchased for continued research.

The photovoltaic system used on WaterLab has a warranty of ten years and guarantees a maximum performance degradation. If future teams notice significant degradation in power production capabilities within ten years (given no physical damage to the panels), they should use the warranty and purchase new panels. Any other panels used on this system should be purchased with consideration to the limits of the MPPT and battery charging current. We recommend switching to a different company for future PV purchases to opt for one of the best solar manufacturers (such as SolarEdge, SunPower, Panasonic, etc).[34]

Appendix A: Requirements and Constraints

Explanation of Requirements Table Format

The requirements table will describe all of the system requirements, customer expectations, and engineering specification that drive the decisions made by our team to design WaterLab. Each constraint was created through careful consideration of the problem that WaterLab tends to solve, as well as the potential issues encountered during the implementation of an off-grid water filtration system. These *Requirement Codes* will be referenced in each of their respective design sections in the document. The following text defines several words used in the requirements table according to *RFC2119 - Key words for use in RFCs to Indicate Requirement Levels*:[35]

1. MUST
This word, or the terms "REQUIRED" or "SHALL", mean that the definition is an absolute requirement of the specification.

2. MUST NOT
This phrase, or the phrase "SHALL NOT", mean that the definition is an absolute prohibition of the specification.

3. SHOULD
This word, or the adjective "RECOMMENDED", mean that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course.

4. SHOULD NOT
This phrase, or the phrase "NOT RECOMMENDED" mean that there may exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.

5. MAY
This word, or the adjective "OPTIONAL", mean that an item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. An implementation which does not include a particular option MUST be prepared to interoperate with another implementation which does include the option, though perhaps with reduced functionality. In the same vein an implementation which does include a particular option MUST be prepared to interoperate with another implementation which does not include the option (except, of course, for the feature the option provides).

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[34] What are the best solar panels to buy for your home?
https://www.solar-estimate.org/news/2019-02-05-what-are-the-best-solar-panels-to-buy-for-your-home-in-2019

[35] Bradner, Scott. *RFC2119 - Key words for use in RFCs to Indicate Requirement Levels*. Mar 1997.

Requirements Table

Code	Description	Subsystem
WL-001	WaterLab **MUST** be small enough to fit in the bed of a truck or large van and **SHOULD** be no heavier than 500 lbs, lightweight enough to be lifted in case of a wheel failure. *WaterLab is going to be used off grid so it must be capable of being transported.*	Body
WL-002	WaterLab **SHOULD** be easy to lift by use of easy to access hand holds.	Body
WL-003	WaterLab **MUST** be resistant against water, corrosion, and other outdoor elements	Body
WL-004	WaterLab **SHOULD** cost no more than $5000, an affordable long term option for water filtration. *WaterLab is going to be used in small, distributed, off-grid application in areas that are not affluent enough for grid infrastructure and therefore need affordable options.*	All
WL-005	WaterLab **SHOULD** be designed to stay off-grid for a minimum of X years. Components, replacements, and maintenance instructions **MUST** be included with the system to last X years. *WaterLab should be a significant replacement to other water sources and filtration needs. Extending the system life of WaterLab should be considered a main priority.*	All
WL-006	WaterLab **MUST** be capable of opening up for component access and filter replacements. *The filters implemented on WaterLab have limited functional lifetimes (denoted in Appendix X) and must be replaced at the end of their limitations or before to ensure proper water quality.*	Body
WL-007	WaterLab **SHOULD NOT** be used to sanitize black water (fecal content). *This water is too contaminated for our system to handle and requires slow, long term filtration methods offered by sanitation facilities with large holding tanks and many step processes.*	Filtration
WL-008	WaterLab **MAY** be used to filter grey water. This is water from your shower, kitchen, bathroom sinks, clothes washer.[1]	Filtration
WL-009	WaterLab **SHOULD** be able to filter water for 15 hours in a day through the use of the power storage system and power generation systems. *WaterLab's goal is to be able to filter water for a community throughout the wakeful hours in a day -- this assumes 9 hour sleep cycles.*	Filtration
WL-010	WaterLab **SHOULD** be able to run completely off of mechanical power. *Time of prolonged low sun exposure will prevent the system from filtering, and therefore failing constraint WL-XXX*	Power

WL-012	WaterLab **SHOULD** be autonomous for filtration, limiting user control to turning on and off water filtration, and viewing system diagnostics. *Limiting user control allows for abstraction and simplicity, which is an important aspect of our project.*	Control
WL-013	WaterLab **SHOULD** have access to intermittent stages for water quality testing between the microscurbber and RO unit, as well as between the RO unit and the UVC LED	Filtration
WL-014	WaterLab **MUST** follow safe operating pressures for individual components to prevent component damage	Filtration
[1] Note: if any of these water sources are contaminated with fecal matter as well, refer back to WL-007.		

Appendix B: Standard Operating Procedures

Power Systems Procedures

Our system uses high voltage and high current systems that can be dangerous to user and damaging to the components if not handled properly. The following list of SOPs must be followed when operating any of the correlated components of the system. Before following any of these procedures, you must already be familiar with the system interconnections by referring to the block diagram and electrical schematic. Because these components are interconnected, you will most likely need to look at multiple documents for handling one component, for example, the battery.

Procedure	**Related/Connected Components**
Solar Panel Testing Procedures	Solar Panels
Testing and Sizing AGM Batteries	Batteries
Connecting the Tristar MPPT Charge Controller	MPPT Charge Controller Solar Panels Batteries
ModBus Communications with MPPT through RS-232 Port	MPPT Charge Controller PSoC 5 Microcontroller

Filtration system

Water Quality Testing

The water quality testing requires using a number of different procedures to test for various contaminants in the water. These tests should only be performed in a lab unless stated otherwise and must be performed by persons with proper training and experience in chemistry and with the chemicals specified.

Procedure	Parameter Tested	Testing Device
Measuring Total Dissolved Solids	TDS	Hach Pocket Pro+ Multi 2
Measuring Salinity	Salinity	Hach Pocket Pro+ Multi 2
Measuring pH Levels	pH	Hach Pocket Pro+ Multi 2
Measuring Electrical Conductivity	eC	Hach Pocket Pro+ Multi 2
Testing Nitrite Concentration	[NO_2^-], Nitrite	DR900
Testing Nitrate Concentration	[NO_3^-], Nitrate	DR900
Testing Chromium Concentration	Total Chromium	DR900
Testing Free Chlorine Concentration	[Cl^-], Free Chlorine	DR900
Testing Total Chlorine Concentration	Total Chlorine	DR900
Testing Sulfate Concentration	[SO_4^{-2}], Sulfate	DR900
Testing Copper Concentration	[Cu^+] and [Cu^{+2}], Copper	DR900
Testing Zinc Concentration	[Zn^{+2}], Zinc	DR900
Testing Manganese Concentration	[Mn^{+2}], Manganese	DR900
Testing Fluoride Concentration	[F^-], Fluoride	DR900
Testing Iron Concentration	[Fe^{+2}] and [Fe^{+3}], Iron	DR900

Appendix C: Budget, Parts, and Components

See WaterLab Final Parts List

Appendix D: Wiring Diagrams

Figure : Control System Wiring Diagram

Appendix E: PCB Design

PCB work to be done next quarter

Appendix F: Component Datasheets and Manuals

Battery		
SunXtender 104AH	https://drive.google.com/open?id=1MCtSw8ETzJoALuLszBncfZuqHLnWRpMM	These batteries are capable of handling the charging current of 2 solar panels, for implementation, we will require 4. (60 lb each)
Trojan J200-RE	https://drive.google.com/open?id=1TEqI4Z-tdEBzt3PmVM5fPoYwjYWclc1W	These batteries will supply the system with the potential to charge and supply the system in the meantime to prevent having to purchase new ones at the moment
Solar Panels		
Sunmodule plus SW 270 mono	https://drive.google.com/open?id=1BaoAOiFy7tfFtd8-5heQhm-rnL2JH1OV	We have three of these in our system
MPPT		
TS-MPPT-45	https://drive.google.com/open?id=1c4R30WQsEUK-LDwDIR7sjwCPjsGnVJUT	Used to charge the batteries, will be implemented with both solar and bike power
Filters		
HydroLogic Tall Boy	https://drive.google.com/open?id=1nj5ahL3Aog6XXJrDeFckyO1C8DHX279E	This is the micro filter scrubber, the secondary filter which is used for sediment and chlorine scrubbing
Keystone standard housing	https://drive.google.com/open?id=1VMZK9VJy_lJTtGGpgXkzm7iuVENcf5nX	This is the filter housing we use but we cannot find documentation on the filter the previous team purchase for this module
Evolution RO1000 Reverse Osmosis Filter	https://drive.google.com/open?id=1NGS3Fr0TgY-2bnUrS9KTHuKja41l0r-thttps://drive.google.com/open?id=1NGS3Fr0TgY-2bnUrS9KTHuKja41l0r-t	
Pearl Aqua 9C UV-C LED	https://drive.google.com/open?id	

	=1RXXq3_iCX8s4Z9Cvb4maI9p4IcZTzBRV	
Others	https://docs.google.com/document/d/1XnPDMkKcc7qy8YXy9k7z8WwhbeNmys97SGERtxI86hw/edit	There are a few other parts without datasheets so we pulled what information we could.
Pumps		
Sensors		
pH Sensor Board	https://drive.google.com/open?id=1u3JZOAxU9nW7UBDlDXRo4pyG7h23_b2M	
pH Probe	https://drive.google.com/open?id=1tgDqVa5WLBbGv96pvPxxBzq6fziJXVI8	
eC Sensor Board	https://drive.google.com/open?id=1F0SdgmLGbZUKVte1KdJFOCvjJUVeSp98	
eC Probe	https://drive.google.com/open?id=1PEmgcFe2XJUYjZ_eI4957Djd9ZO78s-c	
DO Sensor Board	https://drive.google.com/open?id=15lWB8NUddw7hrSXtBWFCs0zfGu1mo1cj	
DO Probe	https://drive.google.com/open?id=1XUIDuVuOM17F4C8ymV1vY5djpZDEUj9M	
EZO Voltage Isolator	https://drive.google.com/open?id=15EeYiGfjeN7ZiSLt71-oWfNB8Zc7rVtX	This voltage isolator is used for all of the water quality sensors. One is needed for each sensor board.
Float Sensors	n/a	
Converters		
DC/DC converter (24 to 12V use)	https://drive.google.com/open?id=1249kAu8g4K62dWelcuxTKIJNU_fJbvY-	

Annotated Bibliography

“Engineering Essentials: Pressure-Control Valves.” *Hydraulics & Pneumatics*, 29 May 2018, www.hydraulicspneumatics.com/200/TechZone/HydraulicValves/Article/False/6411/TechZone-HydraulicValves.

This article describes the need for, and purpose of different types of pressure relief valves. From this article we were able to determine the need for pressure relief valves before the Reverse Osmosis unit. Pressure relief valves divert water flow to reduce pressure once it has reached a certain threshold. That threshold for our system is 80 PSI.

Wimalawansa, S. J. Purification of Contaminated Water with Reverse Osmosis: Effective Solution of Providing Clean Water for Human Needs in Developing Countries. *Int. J. Emerging Technol. Adv. Eng.* **2013.** 3(12). 75-89

Krishnan, S.; et al. Reverse osmosis plants for rural water treatment in Gujarat. **2007.**