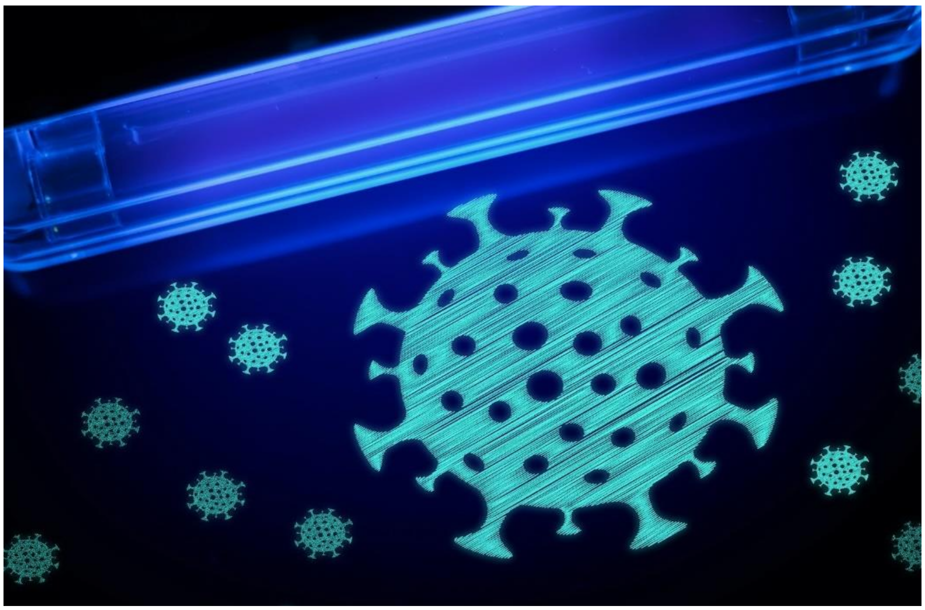
UCF SENIOR DESIGN 2

Title

Portable Unit for Sanitation of Waterborne Pathogens through UV light

(PUVC)



Group Number 4

Group Members:

Joseph Wahlen - Photonic Science & Engineering

Raymond Masciarella - Photonic Science & Engineering

Damian LaRocque - Electrical Engineering

Sannidiyan Rajendran - Computer Engineering

Instructors:

Dr. Hagan

Dr. Richie

Dr. Lei Wei

No current customers, sponsors, or significant contributors

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1.0 Executive Summary

The focus of the following paper is the portable ultraviolet water cleaner. This portable unit for UV sanitation of water or PUVC for short is the senior design project of focus for team four. This project was designed to be an efficient, portable and user friendly unit for water sanitation through UV exposure. This project was brought to our attention because of the recent COVID-19 crisis. Due to the rapid onset of this crisis we began to think more deeply about the cleanliness of our everyday environment not only in the sense of COVID-19 but also the broader range of viruses, bacteria and general pathogens that affect us in our daily lives.We soon came upon the realization that much of the good health we see in the world is a direct result of access to clean water. The WHO estimated in 2017 that nearly 2 billion people a year are exposed to water contaminated with excrement or are unable to have access to proper sanitation measures(1). On top of this dismal statistic the WHO estimated nearly 432,000 people a year die due from tropical disease and lack of proper sanitation (1). We in America and many other developed parts of the world have the luxury of clean, affordable and widely distributed water. We also have water readily available, oftentimes at the turn of a faucet. Not only this but developed countries have localized cleaning systems to ensure the water is potable for all nearby residents. We seek to bring this vital technology to smaller communities or people living without access to a clean water source and who would otherwise have to resort to boiling, sediment filtering, or any other means of primitive water sanitation. Not only this but we also envision utilizing the PUVC for broader application within the developed world as well. The PUVC has many applications as a portable system used to sanitize water for consumption on a local scale where water could be contaminated or exposed to pathogens such as during camping, outdoor sporting events or even at public water fountains.Technologically to accomplish this goal we put together a variety of electronic, optical, chemical and mechanical devices to produce a machine capable of sanitizing water and properly monitoring the cleaning process. The PUVC will work in several stages, first through having an intake pump to pump water into the main tank. This pump will be equipped with filters to clean out any large sediment and reduce overall turbidity of the water. Once the water exits this filter it runs through a smaller high power UV apparatus containing an array of LED's to perform an initial higher power sanitation of the water. Once the water passes through initial sanitation it then lands in our processing tank where additional UV elements will steadily continue to sanitize the water as it sits until it is to be used. To ensure the potability of the water our system will draw a small amount of water from the sterilized tank and then perform a coliform destructive analysis on it. This analysis will be recorded and analyzed by an inbuilt optical system containing devices able to ensure the water meets potable standards. Once the water is ensured to be potable it will then be dispensable from the larger containment chamber. To control the entire device a user interface was created which allows for control of the overall system, monitoring of the water, and modulation of the power and processing speed. The system itself will not be designed to be overly complex as our main goal is to make the PUVC affordable, efficient and portable. There are however several constraints to consider with the PUVC. Two main constraints are to do with the availability of a steady power supply and insurance of water potability. These constraints are major as without a steady feed of power the device will not be operational and without accurate testing the water would not be able to be

ensured that it is indeed clean for consumption. To resolve this potentially glaring issue we will implement a solar panel in the design allowing for charging of the battery and additional cycles to run as well as electronic system measures to modulate power when running in a solar active mode. We also ventured to ensure our design stays portable as we flush out the finer details. To do this we ensured the devices total weight does not exceed 25 pounds empty and its dimensions are no larger than three ft by three ft. There also exists several other constraints for the project dealing with economic, environmental, and social factors. An example of this is that to effectively employ our technology the unit must be cheap enough to reach those without access to clean water, be able to function in non ideal weather conditions, and be easy to use for any person. Although these constraints may not be directly controllable by our team we will seek to put forth a design to best solve all the constraints we have evaluated and can comprehensively offer a solution too. There are already several standards existing for water sanitation that we can draw from to ensure our cleaned water would indeed be potable, the difficulty though is which countries standards to follow. As we are a team based in the United States we will use the American standards set by the SDWA in 1998. These standards far outreach the focus of our project therefore we chose to meet only those standards relating to drinking water, more specifically the revised total coliform rule (RTCR). This standard focuses on pathogens within the water. Coliforms are a group of bacteria and pathogens that are usually not harmful to humans in small amounts, with a few fatal fecal exceptions. E-Coli is one of these fecal coliforms that if ingested can cause severe sickness or even death. To protect the public against this the EPA enforces the RTCR rule through testing water sources using a total coliform test. This test identifies any coliform within the water and with a color changing process indicates the potential presence of fecal coliforms. Due to this fact we will use the RTCR standard to effectively test whether our water is indeed potable post UV cleaning. These standards explicitly outline several pathogen amounts that are permissible within standard drinking water. Of which we have chosen to focus on the general coliform tests which can broadly diagnose the potability of water. In summation the team intends for the PUVC to be a portable, user friendly and effective device to allow those in need an affordable solution to water sanitation through the use of UV light.

2.0 Project Description

The PUVC as stated in the executive summary above is a portable UV water sanitation unit with an active water analysis. The system works through intaking sediment filtered water, sterilizing the water, and then performing a post cleaning potability check before allowing water output. The project was created as a portable water sanitation system for use in scenarios where a volume larger than a gallon is needed to be sanitized for consumption or use. To do this we attempted first to fully understand the problem at hand. The team has put together the following section to outline several project parameters we deem essential to the project's success. In this section we will cover our larger problem statement, motivation, specifications, marketability and overall design flow.

2.1 Problem Statement

There is a lack of consumer products for portable water sanitization systems for medium volume amounts of water. Most available products today are designed for either single person use or large scale communal use. This is especially evident in developing countries where fewer large scale systems are in place and where there is no access to third party sanitation processes.This project seeks to address the need for a moderate water volume sanitation option that allows water in excess of 1 gallon to be sanitized for consumption and use for humans. There are also very few simple methods for laymen to employ to determine that their water is in fact safe to use after sanitization. The products currently available for small amounts of water typically do not have a built water quality analysis system which leaves the user unsure if the sanitization was actually sufficient.This device will offer both a sanitization method and a method of quality analysis on the water. The PUVC includes the use of optical technologies for sanitation and analysis, electronics to drive these systems, and software to make decisions on behalf of the user about the safety of the water. This information will be displayed on a user interface that is simple to operate and understand to ensure that the device is usable by any layman.

2.2 Project Motivation

The motivation behind our project is directly related to the world's new heightened sense of pathogenic awareness. As we all participated in ongoing quarantines it had become very apparent to us not only the effects of pathogens but also how these pathogens spread. We in America are lucky in most cases to never worry about certain pathogens affecting our daily lives. Whereas in the outdoors, in other countries or even impoverished parts of America this idealistic lifestyle is not so. One of the greatest challenges facing citizens of developing countries is the need for potable water not only for drinking but also bathing, washing, and all the other daily water tasks the developed world takes for granted. Potable water allows for not only a healthy populace but also an opportunity to allow these countries to rise socioeconomically as a result of lessened environmental pressures. The PUVC can offer a solution to part of this crisis through providing an effective processing unit for removing pathogens from the water and allowing the populace to begin to focus on other socioeconomic factors. Although the primary motivation for our project is to bring the capabilities of creating potable water to those in dire need. We also see the PUVC having diverse applications ranging from the everyday outdoorsmen to the general sporting populace. The PUVC could be used at rallies, local gyms, or anywhere a guarantee is needed on the cleanliness of the water. Anywhere a cooler like device has been placed in the past we hope to venture to place a PUVC to ensure it is clean. In summation our motivation was to create a portable unit usable by the layman able to effectively clean water and ensure no pathogenic containment.

2.3 Primary Project Specifications

This section will broadly cover the specifications of the methods of sanitation, efficiency, usability and cost amongst other factors. These allow us to uniquely define our project, its problems, and a solution to the problem set each part will create. To ensure our project is to be successful it must meet a variety of design, engineering and marketing specifications. These specifications will offer a description on how each essential part of the project will fit in the overall design and how it will allow our design to be not only effective but also marketable.

2.3.1 Measurable Sanitation

Sanitation will be measured on a pass/fail basis. The presence of total coliforms as mentioned earlier in the executive summary suggests the potential for harmful pathogens to also be present in the sample. Water will be considered clean and safe to use when the water quality analysis yields a negative result for total coliforms in the sample. Any presence of coliforms regardless of the amount will be considered unsafe for human usage. We will employ a chemical test issued by the EPA as well as use an RGB analysis to confirm a positive or negative test. We do not seek to employ any method of specific identification of coliform as this would require a much more robust optical system and remove any chance of portability. In summation we will deem the PUVC able to produce potable water once there is no total coliform detectable, otherwise it will be labeled as a fail.

2.3.2 Efficiency

While the PUVC may be able to run for a very long time when connected to a power grid the true test of our devices ability to impact rural or impoverished communities is going to be its capability to run sanitation cycles while not being connected to a power station or landline. With the implementation of a solar panel the issue of charging the battery will be solved, but it will not be of much use if the charge accrued from the panel is depleted too rapidly. For the PUVC in any manner to be usable to the extent we would like it must be efficient. The project must not only effectively sanitize the water it must also be able to do so for an extended period of time and not be of major detriment to the battery power. We want to allow for the device to be able to clean water for 5 cycles amounting to nearly 50 gallons of water at max capacity provided a 10 gallon holding tank. We would also like the device to run at least one cycle from a solar charge and be able to modulate its power output so that if needed a lower power running mode could be used. Workable efficiency will also direct our design process as each component will be installed with the purpose of performing at as high of an efficiency as possible without overrunning budget.

There are several constraints around maximizing the efficiency of the PUVC. For instance with most electro-optic devices becoming more costly and more difficult to integrate as efficiency is increased the team will have to provide unique designs to combat becoming a device that is too expensive to be commercially used. The team will attempt to tackle these constraints through designing unique software and electronic control solutions to carefully regulate where power is going and how much is being used per cleaning cycle. We also venture to have the PUVC be capable of performing in multiple power modes through modulation of the electronics, more of this will be discussed in the following section 2.3.7 Output Power and Modulation. In closing efficiency will be a major consideration when the PUVC is being designed and the reasoning behind this is due to the fact that without proper power regulation the PUVC will simply be an ornamental gatorade cooler.

2.3.3 Usability by Layman

For the PUVC to be successful in the applications we see it being successful in then the design must be simple enough to operate and control that a user may safely use the device with no technical background. The user should only have to fill the fill tank, empty the sanitation tank and occasionally perform water quality analysis and positive analysis tank cleaning. The water quality analysis will be automated as much as possible to reduce user exposure to error. The user will simply have to choose to perform water quality analysis. The decision as to whether the water is safe to use will be automated by the software designed for the device. The user will be able to read a positive or negative result for contaminants on the user interface. For positive results for contaminants instructions will be provided to the user to safely dispose of the water. In summation the team will design the PUVC to be usable by any layman and will employ software to control any coliform verification decisions.

2.3.4 Solar Operation and Charge Time

As mentioned earlier in the efficiency section we would like for the PUVC to be able to run on solar power while charging. For our project to have long term use beyond a traditional battery life away from a plugin source it needs to have the ability to garner charge from its environment. Due to our want for the PUVC to be portable we had to assess which forms of energy conversion would work best for our project while still maintaining a portable device. After looking through a variety of methods it was decided that solar would be the best route. Due to the lower energy demands of our system after instituting LED’s as a main source we are confident that a solar panel array will be powerful enough to charge the battery to a point of operation. During our prototyping stage in senior design two we will at first prioritize getting these base connections of the solar panel to the battery and also prove through testing that an efficient charge could be achieved. Upon doing so we will then test and quantify a specific charge time that we are able to achieve and perhaps how to improve upon it. In conclusion we venture to not only have the PUVC be able to run purely from a charge garnered from its solar panels but also the device must be able to do so in a relatively shortened time frame of around 24 hours.

2.3.5 Dimensions/Portability

The PUVC must be portable. We do not intend the device to be portable on back when fully assembled but more correctly portable enough to move from one area to another with relative ease and for the device to be able to be moved by two people with ease. As we would like the device to be accessible to those without operational water systems it is essential to design the PUVC to be able to be carried on foot. The PUVC will be designed with the mindset that a large car or truck will not be needed to move the PUVC from one point to another.We do not want our device to be so cumbersome in size that it is prevented from being carried into more difficult areas. The PUVC should be able to fit in the trunk of a mid-sized vehicle as well as be small enough to be shipped. The PUVC must also be light enough so that it will not cause any additional weight problems if it were to be incorporated into any low weight systems such as aircrafts or small boats. The dimensions of the PUVC must also be considered when designing a portable device. When fully assembled we estimate the PUVC to take up no more than a 3 by 3 foot square. This size is subject to change as depending on the circumstances of the installation of the PUVC will be able to be pieced together in a variety of fashions to best fit the needs of the system. The team took inspiration from many other mobile ultraviolet patents as well when thinking about how to pack the UV source in as effectively as possible (11). More discussion of a modular design is found in the following section 2.3.9 Modular Design. In summation the PUVC must be transportable by two people on foot and maintain a size that allows for shipping to remote or unreachable areas.

2.3.6 Cost

Cost is one of the most important factors considered by our team. Not only must it be assessed because this is a self funded student project during a pandemic but also because for the PUVC to be successful it must be cheap enough for those who need it to access it. Due to the recent global pandemic being more impactful on those communities of lower economic standing we deemed it extremely important to provide a reasonably priced device for water sanitation. We wanted the device to be accessible to all, to do so it must be cost effective. This specification not only affected how we designed the PUVC but also which components we chose to go into the device itself. As shown in the table in section 2.5 cost does indeed affect all of the marketing outcomes. Cost affects all of the marketing outcomes because in some way it impacts each part of our ability to market the PUVC and also will dedicate how we are able to create an effective prototype. This is also due to the fact that part selection, especially when it comes to the optical and electronic components, can drastically affect the cost as well as the design of the device. Due to the pandemic there were countless considerations to make in not only product cost but also availability, user support, and product success rate. This forced our team to take a novel approach in selecting components and devices as with the current constraints on shipping and electronic commerce, many companies were forced to increase price while product quality did not and customer service quality fell. We deemed it would be inefficient not only time wise but also with cost if we were to simply buy the cheapest components, wait to test them, and then have to restart the process if given subpar materials. Due to our project centering around creating a working prototype the team took several cost liberties to ensure that the project would be complete within the given time frame. The team will venture throughout the design to catalog and understand where costs can be brought down within the design and come up with novel electronic solutions to reduce complex component requirements. Additionally because the PUVC will have an integrated optical system as stated earlier the team will attempt its best given lead times and our current timeline to outline solutions to lower the cost when the device moves from the prototype stage. In summation cost is one of the most crucial focus points of the design of the PUVC, although due to the current pandemic and availability of materials the team had to take several cost liberties to ensure the PUVC became a working prototype within the given time frame. The team also put extensive work into understanding and outlining where and how costs could be reduced.

2.3.7 Output Power and Modulation

Output power and power modulation are other crucial factors for our project. As mentioned in the earlier section 2.3.1 power is an essential factor in sanitation as without enough UV power the PUVC will not function as a sanitizer. To ensure that enough power is delivered in the system to properly cleanse the water several measures will be instituted and tested during prototyping. As of now we are confident the LED array shown in section 6, lamp shown in section 3, and the sanitation tank shown in section 3 and 6 will in combination have more than enough energy to effectively kill any target coliforms. Modulation of the power is also important because the power output will largely determine the effectiveness of the UV cleaning but modulation will ensure that the battery will not be burned out with improper use. The LEDs and lamp will need to be properly controlled and operated so that they do not simply stay on when not performing a cleaning cycle. The team will also venture to operate the LED array and sanitation tank through multiple power modes depending on the tested coliform. How this would work is the device would perform at first a medium power coliform sanitation, then upon analysis deem whether the device needs increase the power to kill the coliform or if a lower power test can be done as well if the coliform was effectively eliminated. This power modulation will allow the device to potentially run much longer on the same battery charge given not as much energy would be needed for each sanitation.

2.3.8 Implementation Time

For the PUVC to be effective in its target market it must be able to process the water within a time frame that is reasonable for use. Due to there being a large amount of discrepancies in how quickly the water would need to be processed based on the local situation, a variable implementation and operation time must be available. The team had already considered power modulation not only for its capacities to save battery life and offer multiple cleaning modes but also how it can be applied to lessen implementation time. Due to the teams focus on power and power modulation in the initial design the implementation time will also be given great consideration and time reduction will be a major design theme. The team is confident that a full 5-10 gallon tank can be effectively sanitized in under 30 minutes. This time is actually far greater than we estimate to be needed with the current setup to perform sanitation but because we will not be able to control the systems the PUVC will be integrated into, we would like to establish a baseline cleaning time. This time may also change as more testing is done to verify exactly how much time it takes for us to effectively clean our water samples. It should be noted that the implementation time could drastically vary given the amount of filtering that must be done on the water. For instance water taken from a clean running stream in america would take far less potential time to sanitize than a stillwater system in a developing country contaminated with potential fecal coliform. Due to this the team is going to again design the PUVC with specific characteristics such as a portable and modular design so that if more preprocessing is needed the PUVC will be easily integratable. The team will also venture to reduce implementation time through improving the efficiency of the reagent testing, electronic efficiency, software usability and power delivered through the optical design. In summation the team ventures to design the PUVC to be capable of effectively cleaning 5-10 gallons of water within a 30 minute time period and given the water is not contaminated by fecal matter in a time under 15 minutes.

2.3.9 Modular Design

Our end goal for the PUVC is to have a portable and modular design for incorporation into multiple different water flow systems. For the PUVC to accomplish this it must have a design that allows for easy disassembly and parts swapping. Although the UV elements will not be subject to change as they will be embedded in larger designs, the components containing the LEDs must be easily movable and replaceable. To achieve this the team moved forward through prototyping with the mindset that each essential part must be separable from the main unit unless absolutely necessary. To do this the team designed the PUVC in five essential parts. These parts are a detachable pump and filter array, initial high power cleaning array, the sanitation tank, analysis tank and user interface. Each of these parts will coalesce to perform the cleaning and operation but the team does not venture to have each unit be self supporting. We have also left out of mention smaller add ons such as the solar panel and other attachables that could aid the PUVC in operation, these will be discussed later in the following research section 3.0. In summation the team designed the PUVC with the general theme that it should be as modular as possible to allow for greater portability and environmental adaptation.

2.4 Standards and Requirements Specifications List

- The PUVC must meet the SDWA standard that dictates a level of zero coliform per 100 ml of water to designate it as potable
- The PUVC must be able to kill pathogens
- The PUVC must be able to show proof of sterilization of the water through means of testing
- The PUVC must be able to sanitize water in under 30 minutes from time of water input
- The PUVC will have an user interface display that provides information about the quality of water and state of the system
- The PUVC will be no taller than 3 foot
- The PUVC will be no longer than 3 feet

- The batteries must be rechargeable and recharged by solar power or wall outlet
- The PUVC must have a minimum of 4 operating hours per charge
- The batteries must be charged at a current of 20% or less of the battery's Ah rating to preserve the cycle life of the battery
- The PUVC must be able to be powered both by a standard wall outlet and by battery
- The PUVC must be able to vary the power based on the available amount of battery charge remaining
- The total cost of the system must not exceed $1500
- The PUVC must be portable
- The PUVC must be modular
- The noise produced by the PUVC must be under 40 dB
- The PUVC must be durable and able to withstand rain.
- The PUVC must be under 25 lbs
- The PUVC must be designed in such a way that there is no chance of the water coming in contact with the electrical components

2.5 Project Marketing Specifications

Shown below in table 1 is our project's quality of house table. This table shows the relationship between our marketing and engineering requirements that we explained in the previous section. In order for our design to successfully work and be a marketable device we must achieve a reasonable balance between our engineering and marketing requirements. The engineering requirements focus on physical design parameters the team designates as essential to meet for the proper creation of the PUVC. These parameters are open to change as due to the COVID-19 epidemic there has been extreme difficulty in getting proper lab space and equipment for optical testing as well as performance testing. The marketing requirements are specifications that the team designates as essential to the success of the PUVC as an actual product. For the PUVC to be sellable it must appeal to its end user, to appeal to its end user the PUVC must satisfy several marketing requirements while also not infringing too greatly on the engineering requirements.

In order to design a device to match the requirements and specifications listed, it is important that the tradeoffs between these requirements are known and are weighed accordingly. It is up to the team to develop a strong product that will incorporate a balance of each market and engineering requirement. From analysis of the quality of house diagrams, the most pertinent relationship will be between the low cost and the high efficiency. The team will have to function to maximize the accuracy and efficiency of the device while working within the cost constraint. As of now we estimate that a functional device could cost under $1500 dollars and while also being able to cleanse the water of 99% of waterborne coliforms in under an hour.

Table 1: Project Quality of House and Marketing Analysis

Engineering Requirements →		***Efficiency***	***Output Power***	***Implementation time***	***Weight***	***Cost***	***Dimensions***	***Solar Charge Time***
Engineering Targets		***100%***	***40mw-5 Watts***	***<30 minutes***	***<50 pounds***	***<1500 $***	***Fits in 3X3 foot area***	***<6 hours***
		+	+	-	-	-	-	+
Market Requirements ↓								
Low Cost	+	↓	↓↓	↑	↑	↑↑	↑	-
Portability	+	↓	↓↓	↓	↑↑	↓↓	↑↑	↑
Kills Pathogens	+	↑	↑↑	↑	-	↓↓	-	-
Ease of Use	+	↑↑	-	↓	↑	↓↓	↑	↓
Capable of multiple power modes	+	↑↑	↑↑	↑	-	↓↓	-	↑↑
Durable	+	↑	-	-	↑	↓	↑	↑
Modular	+	↑	↑	↑	↑	↓	↑↑	↑↑

Legend For Trade off Matrix:

- \+ : ***Positive Polarity***
- \- : ***Negative Polarity***
- ↑ : ***Positive Correlation***
- ↑↑ : ***Strong Positive Correlation***
- ↓ : ***Negative Correlation***
- ↓↓ : ***Strong Negative Correlation***
- ***- : No correlation***

2.6 Software Logic Flow

For our device to operate effectively there must be a set and logical flow to the software that controls it. To ensure that moving forward we have a good idea as to how we want our system to manage itself we decided to create a flow chart illustrating the logical steps our software will take. Shown below in figure 1 is a block diagram of the coding software we will be planning to use for the PUVC. The operation will all start from when the device is turned on and the flow of water is initiated. At the same time the flow is initiated a water sensor at the top of the sanitation tank becomes active to monitor the water level in the tank. The software will then continue pumping the tank with water until the tank is full. While the water is being pumped into the main tank it undergoes its first round of UV exposure. Once the tank is deembed full the UV sanitation will then occur as the other LED's in the tank turn on to effectively eliminate any remaining pathogens. Once the sanitation cycle is completed the device will then drain a small amount of the sanitation tank into a holding vessel for RGB testing and coliform testing. The software will then allow the user to see the coliform test if deemed successful allow for output from the tank. If the check is not deemed successful then the program will restart the UV cleaning cycle.

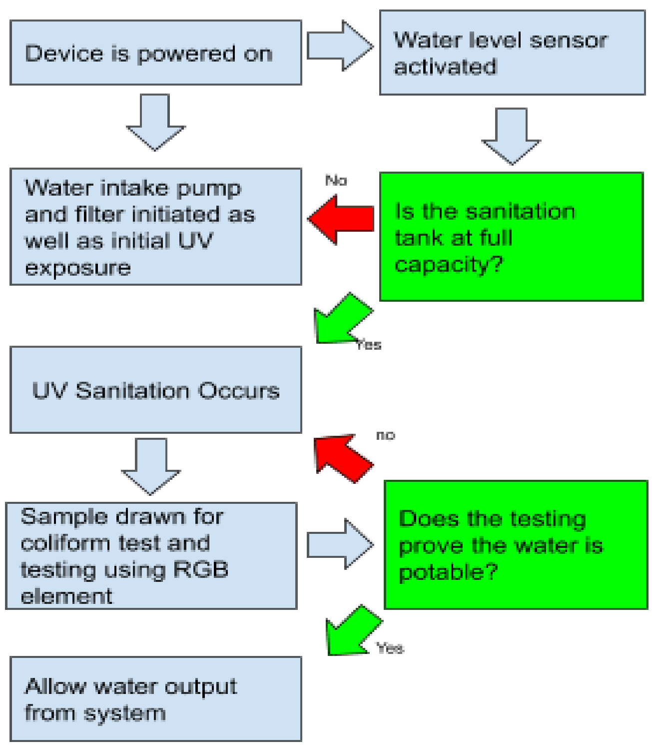

Figure 1: Flowchart showing PUVC Software Logic

2.7 Overall Project Design Flow

To better plan how our project in the end would work and so that we could more effectively understand which team member would be responsible for which part, we decided to create a block diagram during each phase of our design process. The diagram shown below in figure 2 highlights our logic when we initially approached this project and how we decided to split up the components of the project so that it could be the most efficient, user friendly, and possible to complete by us within our given time frame. Shown below in the block diagram figure 2 is how the water could be taken from each stage of the device to the next and what is performed at each stage. At first we had the idea to have a three tank system to allow for easy separation of each process and to avoid any cross contamination. We want the reader to also keep in mind during the evaluation of this design that it is intended to be modular, that is each part could be separate from the central unit. The block diagram also shows where initially we thought pumps could be installed. When thinking about applications we would also like the readers to keep in mind the PUVC is again meant to be modular, any intake pump can be replaced with a freshwater input or output from almost any given water system to create a more unique system.

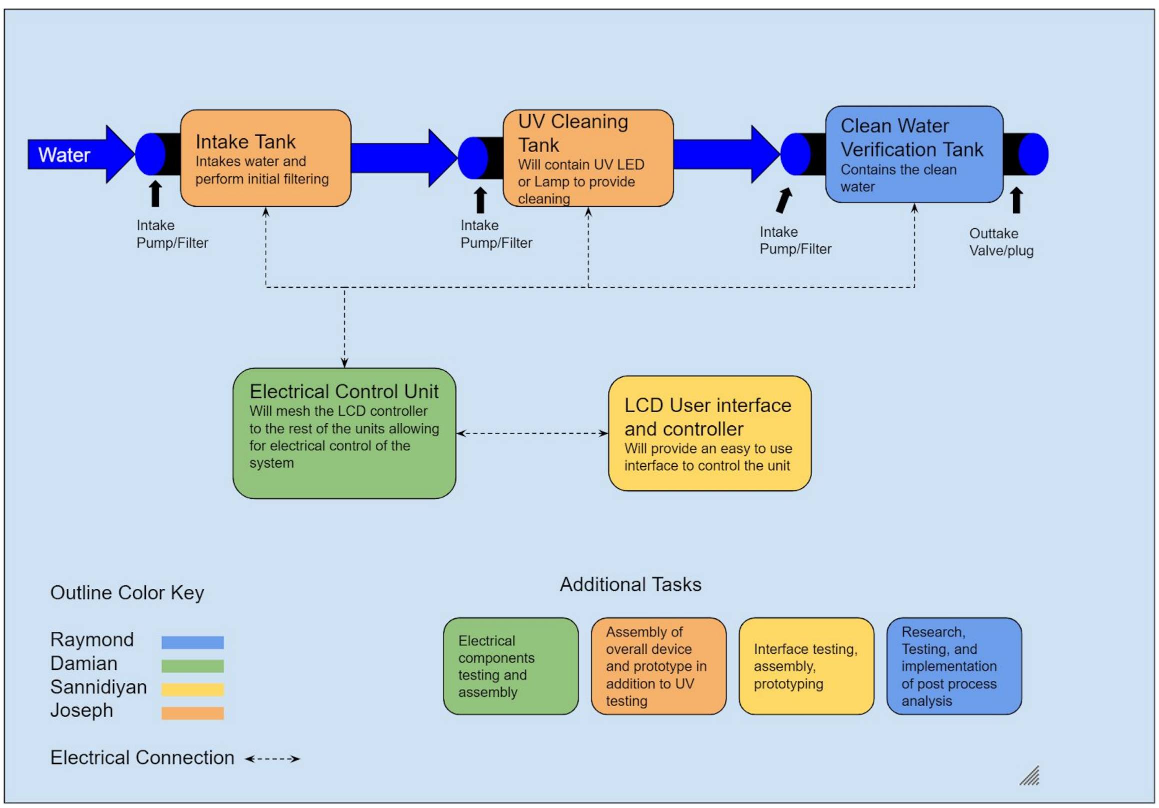

Figure 2: Initial Block Diagram of UV sanitation system

Shown below in figure 3 is the final diagram created by our team for senior design two. As can be shown below the design has changed overall from a three tank system to a single tank system. We also removed the indication as to where the pumps will go because we believe with a one tank design the pump array could be varied depending on the intended application of the PUVC. Our final diagram shown in figure 3 below highlights some of the major changes we have implemented as well as expand upon the principles of our original design. The final design diagram contains how we will attempt to split up the work for the various components as well as their design and assembly. We attempted to define as effectively as we could our current design purposes and solutions to our problem statement. As can be seen in figure 3 below, our final design flow involves an initial high power UV array of diodes, a water sanitation tank, analysis tank and supporting electronics and user interfacing software. The color coordination of who will oversee what parts of the PUVC are the same as in figure 2. There is also the addition of the solar cell to power the unit and who will oversee its installation. As stated earlier it must be kept in mind that these are simply best fit guesses, as testing progresses and the design is implemented fully the overall design flow will change and different members may contribute more to each part than originally established. Overall figure 3 shows our best estimate as to how we were able to divide and conquer the PUVC prototype during these difficult times.

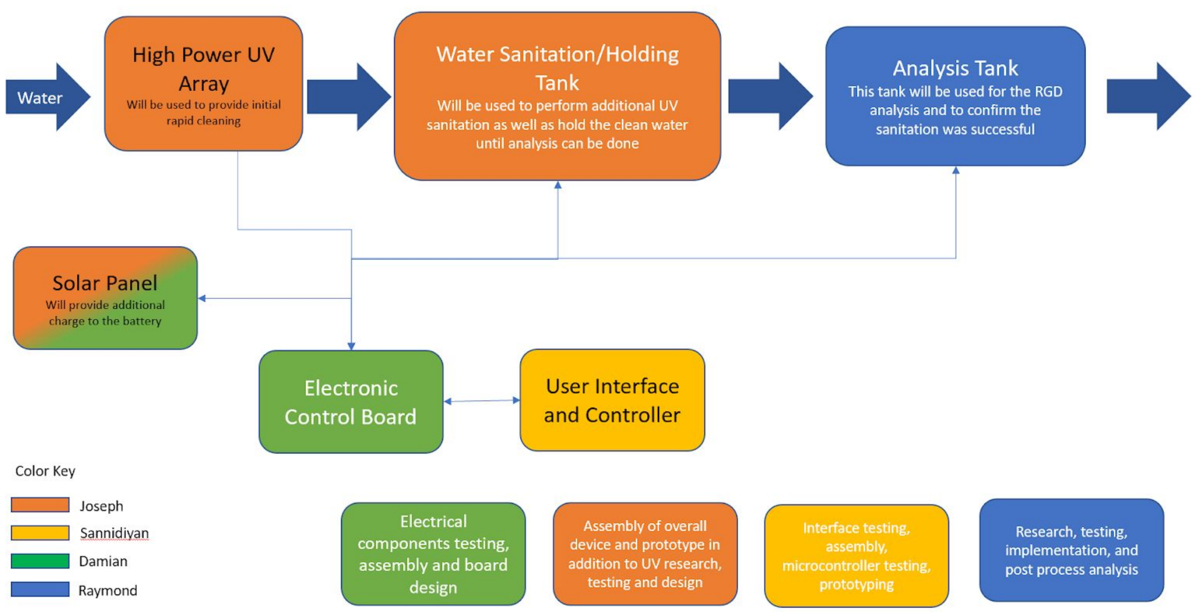

Figure 3: Final Design Block Diagram

3.0 Research

All designs must start somewhere. A good first step is to start by assessing a project's feasibility, useability and marketability. If a product is not properly evaluated at first then further development of that same project could run into major hurdles. These hurdles could force a delay and reorganization or even worse, a failure to develop the product. To start our project we began with extensively researching the capabilities of using UV in sanitizing water, airborne illness and many other applications to get a good idea of how we could uniquely apply the cleaning power of UV to our project. Not only this, but to ensure that we are understanding the process of how the UV actually kills the virus we set to understand the underlying mechanism that allows UV radiation to be lethal to pathogens and bacteria. To ensure our project was successful each teammate had to independently design and then collaboratively build multiple essential parts while ensuring these parts would seamlessly fit within the overall project. In totality as further discussed in this section our project required a vast amount of individual and combined effort in not only UV research but mechanical research in the movement of water, interface research for increased usability and electrical research to ensure all the parts worked together.

3.1 Existing Projects and Products

As stated earlier, clean water is an essential need to all humans. The addition of a portable and effective water cleaning system that also takes care of the invisible pathogens could be live saving in many applications. Not only this but there is an already existing market for which we see a hole the PUVC could fill. With the use of a portable UV water filtration system, clean water could become a real possibility for many and not at a small volume or high price point. Not only this but our additional research gives us the confidence that our project could be easily expanded upon so that a large amount of water could be processed and at a cheaper price point than currently commercially available.

3.1.1 Steripen

The Steripen is a small portable UV probe, shown below in figure 4, that can be placed inside of small bottles or jugs of water to be used as an effective pathogen sanitizer. The steripen works through using a small UVC lamp protected by a quartz cover that acts as a plug to any 24oz or below drink. Then upon activation within 48-90 seconds it is able to purify the water of on average 99.8% of all harmful pathogens(21). The Steripen has received large amounts of success amongst backpackers and mountaineers due to its portability, effectiveness and ease of use. The Steripen is shown below in figure 4 being used to clean a cup of water and also being used to clean a bottle as well. As can be shown below the Steripen is mainly used for small amounts of water. We wanted to expand upon this idea to create a more high volume portable water sanitation unit. The steripen also sets a good baseline for us as to how much energy is truly needed to effectively kill pathogens and waterborne bacteria as many research studies have been done on the effectiveness of the Steripen.

Figure 4 : Steripen with intended application
(Reprinted with permission from ILT)

3.1.2 AquaSana Well Water Rhino

The AquaSana Well Water Rhino (WWR) is a 500,000 gallon UV water processing unit.We viewed this device as an example for an extremely high volume but effective water sanitation unit. This unit contains five filters as well as a UV lamp for sterilization. The WWR is used to process municipal and ground water for use in family homes or small companies. The WWR works through connecting into a prebuilt plumbing system and then performing a variety of water filtration and sanitation techniques such as sediment filtration, salt-water conditioning, soluble heavy metal filtering and active carbon filtering. All of this filtering is done before the water is then exposed to a high wattage UV-C bulb located in the silver capsule on the left of the device shown in figure 5. The WWR in its entirety is also shown in figure x to show the amount of filters in place for the system to be capable of dealing with its 500,000 gallon capacity. The WWR is far more able to deal with heavy metal contaminations as well as hard water contaminants than we seek the PUVC to be but it still provides a good example for an effective water filtration system for very contaminated water. Although we did not want to mimic the volume of water processable by the WWR we did view the device as an excellent example of the potential of a UV-C system. In totality the team used their designs as an example for how thoroughly we should clean our water pre-sanitation to ensure that our UV is effective and also how UV could be used to effectively treat large amounts of water rapidly.

Figure 5 : AquaSana Water Rhino UV water sanitation unit
(Reprinted with permission from Clean Water Store)

3.2 Relevant Technologies

To better understand the potential applications and design problems we may encounter it was in the teams best interest to first research and understand several technologies that we would draw from. These technologies would allow us to better understand industry and market standards so that we could better plan the project and avoid pitfalls. We chose to investigate technologies directly related to the PUVC and its essential components. In the section below we will outlaw the primary researched support technologies and applications of UV based technology on a broad scale.

3.2.1 Optical Methods of Water Sanitization

Water sanitation through optical means is a fairly simple process that has been used for numerous applications since the early 1900s. The main means of water sanitation through optics is using ultraviolet germicidal irradiation (UVGI). UVGI is able to sanitize many pathogens through acting as a mutagen to the bacteria, viruses and many microscopic organisms at a cellular level (12). Germicidal effects of near UV wavelengths were first discovered in 1878 by

Arthur Downs and Thomas Blunt when they tested the germicidal effects of using short wavelengths to sanitize bacteria (15). UVGI is able to perform germicide because they are at a wavelength that is highly absorbed by nucleic acids. UVGI in essence is electromagnetic radiation that is in the range of 100-300 nm that is able to neutralize the ability of microorganisms to reproduce by causing photochemical damage to the sensitive DNA contained in the nucleic acids of the cells (14). The germicidal effects of UV peak at a wavelength between 230-270 nm, this peak corresponds to the effective absorption max of bacterial and pathogenic DNA(15). UV radiation itself can be defined in three unique categories that define its applications. These three designations are UV-C, UV-B, and UV-A. The wavelength ranges, applications and germicidal efficacy of these three wavelengths are shown in the table 2 below.

Table 2: UV Comparisons

UV Radiation Type	*Wavelength Range*	*Applications*	*Germicidal Efficacy*
UVC	180 - 280 nm	Sanitation of air, surfaces, water	Strong
UVB	280 - 315 nm	UV curing, printing, dental	Mild
UVA	315 - 400 nm	Fluorescence activation, medical applications	Low

After analysis of these key wavelength differences and keeping in mind that our system is a water based system we then decided to specifically focus on the use of UVC light for germicide.
The effectiveness and processing capabilities of UVC systems are extremely varied due to the wide nature of application. Due to this the team decided to narrow the focus of our research to primarily UVC applications of water cleaning. The first application of large scale UV cleansing was done in France in 1908 when UVC producing mercury lamps were used to sanitize the municipal water of Marseille, France (15). In modern times there are applications being produced almost daily from water sanitation to pharmaceutical cleansing and more. UV is an extremely powerful tool for use in sanitation of water, air, and a variety of surfaces. For the PUVC we tried to harness this power to provide an efficient and effective solution to pathogen removal. Water sanitation can be performed through a variety of optical methods using UV. These methods can be as simple as broadband exposure or as complex as having an integrated optical system targeting specific pathogen absorption bands. The main way that products are sanitized through light is through the use of a UV bath method. This method is similar to regular cleaning using water but instead the volume of the area is filled with a uniform distribution of light able to effectively sanitize any waterborne pathogens. Modern technology has allowed for much greater control over the profiles of light distribution that are producible. The team is going to attempt to take advantage of this through the use of a UV dispersion matrix capable of redistributing LED UVC light into a more concentrated area. In summation UVC exposure through the use of LEDs and UVC lamps will be the primary method the team pursues to provide the PUVC with water sanitation capabilities.

3.2.1.1 UVC LEDs/Lamps for use in sanitation

UV LED's and lamps are a crucial technology in the pathogen sanitation industry as mentioned in the previous section. Without these devices much of the industry would not exist and many more expensive chemical processes would have to be used for the same sanitation (5*)*. The first commercially available UVC lamps were produced by Westinghouse in the 1930s for use in hospitals and soon were being used for a variety of novel sanitation applications (15). UVC lamps have already been applied in fact to large scale water sanitation as mentioned earlier for many years. This is another reason the team was able to identify a niche market where UVC sanitation was needed for medium to low commercial volumes of water as opposed to a massive industrial system. Germicidal ultraviolet lamps (also referred to as UVC lamps) are short to medium wave, low to medium pressure lighting tubes that produce ultraviolet wavelengths lethal to microorganisms. These lamps operate through the use of embedded mercury or free mercury within the system that is excited within the tube through the use of an electric current. Depending on the pressure of the tube the wavelengths emitted by the tube can vary. As the electric current and pressure can be varied so can the wavelengths produced by the lamps. The team decided for our application it was best to focus on lamps that produce most of their energy within the UVC and UVB bandwidths as these had the greatest germicidal effects. The team would also only focus on the use of the UV wavelengths to kill pathogens, not how the lamps or LEDs can be manipulated to increase output of ionizing wavelengths. The powers produced by the UVC lamps available in the current market far outreach the smaller volume of water the PUVC will need to sanitize. This will allow the PUVC to drastically reduce its processing time when using the UVC lamp as the greatly increased power delivery will cut the time needed to kill selected pathogens down greatly. Further discussion of the UVC lamp characteristics we decided on for the final design and our final lamp selection can be found in section 3.3.2. UVC LEDs produce UV light similar to that produced in UV lamps although the generation methods are far different. Where LEDs have advantage is their spectral distribution is far more concentrated than that of UVC lamps, this allows for much more specific coliform targeting. LEDs have this advantage because of their generation method. The UVC LEDs the team will investigate will most likely work by . UV LEDs themselves have extremely broad application. The LEDs can be applied to optical data storage, communication, biological agent detection, polymer curing and more. LEDs are also smaller in profile allowing for a more diverse incorporation and allowing for the device dimensions to be reduced. Further information on how the team will incorporate the LEDs and which LEDs the team has decided one can be found in sections 3.3.1 and 5.1 respectively.

For our project we had to review many different types of UV LEDs as well as UVC lamps. Both provided good solutions to our need for a UV source, although both have far different power levels and output characteristics as discussed. To find out which was best we first referred back to our research and searched for devices that produced wavelengths in the range of 230-300 nanometers (UVC) as this is a provenly effective wavelength for killing pathogens. The team will primarily buy and test lamps and LEDs that produce wavelengths within this region. Given proper time to test this may change if the targeted water contains pathogens more absorptive in the UVB or UVA range. As the design process continues the team will evaluate the LEDs and lamps performance versus their sap on energy demands. If it is concluded that either or is ineffective then the team will focus on producing a solution to incorporate either more LEDS or lamps to provide sufficient power. UVC LEDs also offer a great advantage due to the higher power. It has been shown in previous studies there is a direct correlation to the power of the UC radiant and the effectiveness of the sanitation (20). In conclusion going forward the team will be focusing on incorporating UVC LEDs and lamps as the primary sources for UVC light enabling the PUVC to perform as a sanitation unit.

3.2.2 Optical Methods for Coliform Detection

Discussed below is a variety of methods that were investigated as possible solutions to the problem of verifying that the coliform is indeed dead from UV sanitation. This section will cover all forms of coliform detection the team deemed necessary to understand and also explore the underlying principles behind each detection method.

3.2.2.1 Microscopy

One of the simplest optical methods to detect coliforms in water is microscopy. Microscopy is simply the use of microscopes to view objects, bacteria in this case, that can't be seen with the naked eye. While microscopy can produce accurate identification. It requires some expertise to understand what the user is observing and whether it's harmful or not. This method was considered for our system but was ultimately scrapped because the knowledge required to identify bacteria violated our constraint of the system being operable by a layman. It also would be difficult to build a system with powerful enough resolution to view some smaller coliforms such as E-coli which is on the order of 1-2 micrometers with a radius of about .5 micrometers given budget and equipment constraints. The figure below shows the rod-like shape of coliforms. Shown below in figure 6 is a magnified E-coli photo.

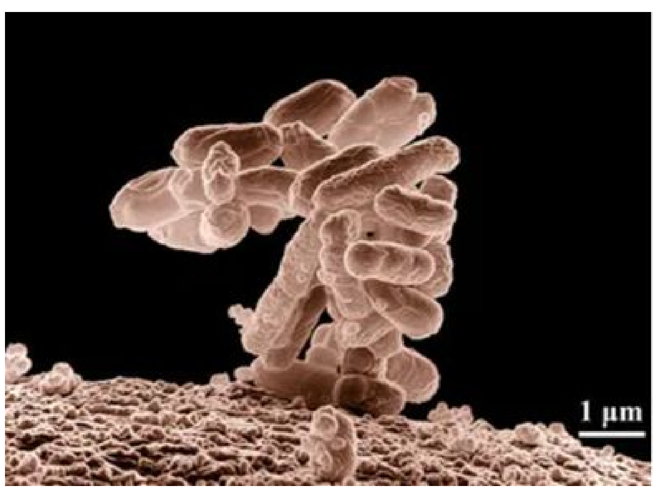

Figure 6: Low temperature electron micrograph of E. Coli magnified 10,000x

(Reprinted with permission from the United States Department of Agriculture)

3.2.2.2 Image Processing

There are some new cutting edge technologies being developed to automate microscopy techniques. These techniques involve 3D scanning a water sample and taking many images of particles in the water. These images are then processed and have their spatial parameters decomposed such as area, length, perimeter, eccentricity, and convexity. Other parameters are considered as well such as contrast, light-scattering, absorption, and features extracted from the Fourier transformed image. Software algorithms consider all the parameters analyzed and group the particles according to how they match the features of known bacteria and contaminants. The results of these scans provide rapid, almost real time detection of pathogens for on-line water treatment systems. These systems can differentiate between bacteria and abiotic particles and provide results much faster than existing chemical techniques without destructive analysis. They also require much less maintenance typically associated with water treatment. Existing methods require weekly and sometimes daily maintenance.

This type of system would be very robust but is very complicated, expensive to develop and would be quite difficult to make compact enough to fit in a portable system as envisioned. This type of method would be better operated in water treatment plants where size and portability aren't a constraint. The expense involved in development also makes this a non-viable method for a low cost consumer device.

3.2.2.3 Raman Scattering

Raman scattering is a spectroscopy that uses laser light to determine the vibrational modes of molecules. Molecules have unique vibrational modes of their electrons that can be used to identify them. The laser light interacts with vibrational energy of the molecules and the energy of the photons is shifted either up or down. The shift in energy can be processed to determine the vibrational modes of the molecule. A typical raman scattering system consists of a monochrome light source, usually a laser, a lens to collect and focus the light from the laser, a monochromator to ensure the light interacting with the molecule has as small of a linewidth as possible, various filters and and a detector. The detector views inelastically scattered light to determine the vibrational modes. Inelastically scattered light refers to the fact that the energy of the photons is not conserved, the photons either slightly gain or lose energy when interacting with the molecules.

3.2.3 Chemical Testing for Water Quality Analysis

To detect coliforms in the water sample a chemical test will be used. There is a wide range of chemical tests available for the detection of coliforms ranging from high grade lab tests to low cost consumer home test kits. Our design will rely on the cheaper at home use test kits.

The way these tests generally work is by placing a water sample in a bottle containing a nutrient blend that may or may not cause an immediate color change to the water. If coliforms are present they will consume the nutrients and the sample will change colors. Depending on the temperature the sample is stored at the result can take anywhere from 24-48 hours to show. At high temperature (35 degrees Celsius) the results can show in 24 hours, at room temperature the result can take up to 48 hours. The time required to show a result is undesired for the application of our system but is a necessary tradeoff due to budget and equipment constraints. Shown below in figure 7 is an example of a coliform identification test.

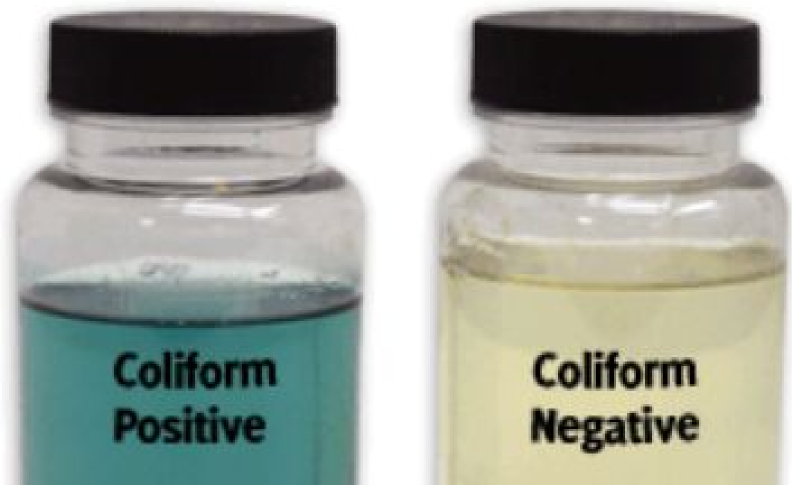

Figure 7: An example of two samples with a positive and negative result for coliforms

(Reprinted with permission from Clean Water Store)

It should be noted that the detection of coliforms alone does not indicate that the water is unsafe to use. Most coliform bacteria are harmless, however the presence of coliform bacteria can indicate the possibility of harmful coliforms such as E-coli being present in the sample. Some home test kits can also identify the presence of E-coli specifically. For these types of tests a sample showing a positive result can be viewed under a UV light. If the sample is fluorescent this typically indicates the presence of E-coli, a pathogen that is dangerous to humans.

3.2.4 Electronic Components

To ensure that all of our components would work together, not burn out, and function for a long duration work had to be done to better understand what key electronics would be important for the PUVC. In this section the team will discuss our key electronic components and the information we deemed essential to know about each product to maximize the effectiveness of the PUVC.

3.2.5 Solar Panels

Solar panels provide a unique solution to a few glaring problems in our current design. Such as the ability to run without the use of a wall plug in and after the battery has been depleted. The solar panels will allow for the battery to be recharged without having to be plugged into a wall unit. The solar panels will do this through the use of photovoltaic cells (PVs). PVs are able to harness the energy from radiation from the sun through the process of photon absorption and conversion into electrons often known as the photoelectric effect. More specifically the photoelectric effect is the emission of a single electron from a surface material when that material is impinged upon with a radiation high enough to knock off an outer shell electron. These photoemissive materials then produce photoelectrons that can be harnessed and used as DC power or converted into AC. The photoelectric effect was first discovered in 1839 by French scientist Alexander Becquerel and the first silicon PVs were created by Bell Labs in the 1930s. Typical PV's are only able to exchange one electron for one photon regardless of the semiconductor material or band gap energy requirements. Only recently have scientists been able to develop solar cells with PV's capable of harnessing two electrons from a singular photon exposure (13). This additional energy could provide the unit with enough charge to run the UV cycle more times. This also would increase the portability of the device as less more efficient solar panels could be used for use of the device when not near any electrical port making the device much more portable. Solar panels are currently one of the most reliable, renewable and popular forms of harness environmental energy. Solar panels also run on DC power as discussed earlier and similar to our battery. This makes it very easy to integrate the solar panel as an effective charging unit for the PUVC. For our system we will be focusing on 12 volt solar cells or PV 12 for short.The PV 12V system is used in many applications. Moreover, when designing a 12V system, every device in the system must be in 12V rating or have accompanying electronics to modulate the voltage. Furthermore, the components in the same rating voltage level are extremely critical because they help the system to prevent potential damage. Since the voltage ratings are at a sizable and feasible level for our application. The PV 12 provides a lower cost in a wide range of applications and also brings more efficiency to the system. Finally, our charge controller must be at 12V rating level. On the other hand, we ensured that the inverter DC-AC will only accept 12V DC as input and convert to 120V AC output if needed for a UV lamp. Shown below in figure 8 is a popular fold out solar panel known as the Mobisun as well as a basic diagram of photovoltaic cells for reference.

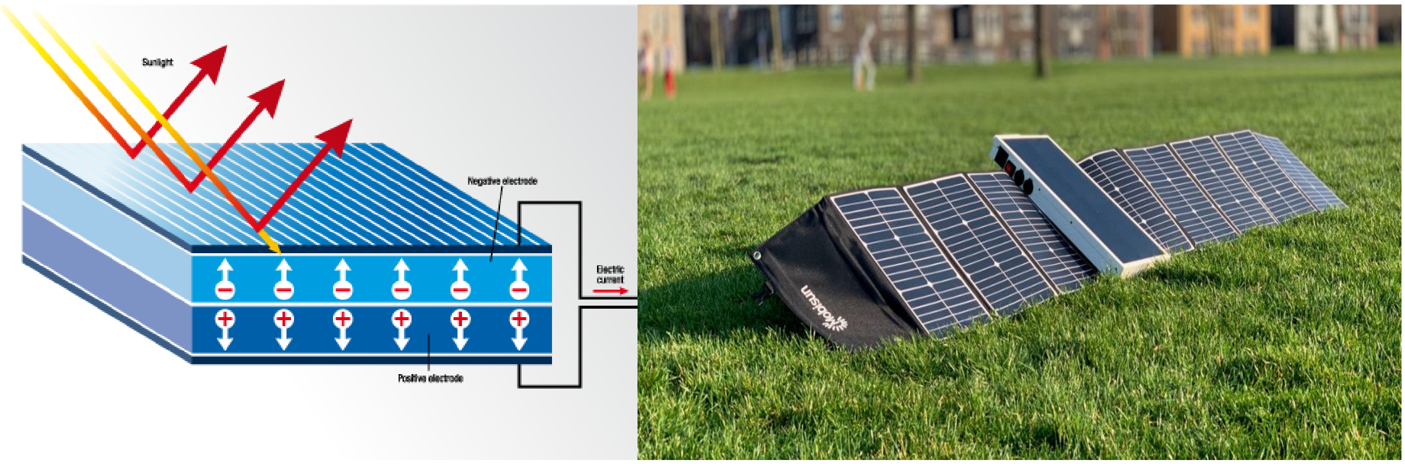

Figure 8: (left) Shown is a basic diagram of a solar panel as a photovoltaic cell. (right) Shown is a typical portable solar panel array.
(Reprinted with permission from Mobisun)

3.2.5.1 Off Grid vs On Grid Solar Panel Considerations

An off grid solar panel is a solar panel that can support itself without the need of additional charge or voltage from a landline. These solar panels are able to complete this task through the use of photovoltaic cells. Photovoltaic cells are able to harness the radiative energy from the sun and convert photons into electrons. Most typical cells operate either as an integrated grid panel or a disconnected panel. Our design requires a mixture of these which will introduce some electronic constraints that must be designed for. Since we would like the system to not require any connection to a utility line, the installation could become more simple and it can be a proper choice for some eco-friendly applications which do not require any power supplied from local utility. Mostly, this system is preferred to be placed where the utility pole or grid cannot reach too. These types of systems are very common in rural areas or remote from cities, where the power grid does not reach. One of the main factors making the off-grid system preferable is the independent characteristic. Since the system is not installed on a certain fixed location, it can be mounted on any place for its functionality purpose. This allows for the PUVC to become more portable as it would not have to rely on a grid connection for operation. The system is completely independent and thanks to that you can store the energy you want and use it in the evenings and during the cloudy days. Moreover, most of the time, rechargeable backup batteries are always viewed as a better solution for power storage systems than any other system. Usually, the backup power batteries have a wide range of selections based on the demand of the loads and the budget for the system.

On grid panels are interconnected to the electricity grid. In other words, all the energy generated by the solar panels is injected directly into the local grid and they operate in parallel with the grid. In most cases, for interconnected systems, you must make a contract with your local electricity company that verifies that your entire system complies with the regulations since the energy you generate sends it to the national grid and it is fundamental to guarantee its quality. Since the system is tied to the grid, it provides the dual solution to both problems in powers, power outage and extra power supplied. The extra power supplied from the solar panel can be directly transferred into the grid when the loads are over supplied, and with this solution, the potential damage to the device due to overpowering supplied can be reduced and no unused power will be wasted. Furthermore, for the power outage, the load demand will be supplied from the power from the utility grid if the power from the solar panels are not generating enough for the application to operate. These systems are sometimes cheaper because you do not need a battery bank, which is sometimes the most expensive device in an isolated system and those that require the most maintenance. The batteries are not needed because most of the power flow actions take place between the grid and the loads. The cost of having a grid connected solar power system would be less than the stand- alone system since the batteries are not included in the system. The grid-connected system can be less in economic aspect but it may require more in engineering technical aspect which explains why all the large-scale applications such as the power generation system always require the system of grid-connected.

In summation we endeavoured to compare the various solar technologies and which could work best for our unique application. There were several parameters to assess such as charge time, cost, lifetime, amongst others and these constraints must be researched before a purchase of a solar panel is made. Based on our current research up to this point we are expecting the PUVC to employ an off grid solar panel due to our want for the system to stay portable. This could be subject to change if the power requirements of the system due to new electronics exceeds the amount of power we would need to be able to garner from the solar panel in a 24 hour period.

3.2.5.2 Charging batteries through Solar

There are a variety of methods to convert photoelectrons into a battery charge. For the PUVC we chose to use solar panels to charge a battery as it proved to be the easiest renewable energy source to integrate. Solar panels offer greater relative efficiency and allow the PUVC to become more portable. Most solar panels have the simple integration of connecting it to a charge controller to avoid excess charge occurring in the battery and then simply wiring it to the battery based on the battery specifications. Once the charge controller is in the place the DC to DC connector is simple. To ensure excess charge once the battery is full is not wasted we will attempt to create a energy banking system so that all accrued energy is used for sanitation.

3.2.6 Electric power system

Some of the major factors to be taken into account when choosing a power supply system are power requirements of the devices and components that make up the project, portability, whether AC or DC power is required, compatibility with devices, efficiency and cost, in no particular order. Each of the various forms of power delivery systems have their advantages and disadvantages and it is up to the designer to decide which factors should be prioritized to suit the goal of the project.

Some of the many ways to power a project include wall warts, batteries, DC power supply and USB power. Wall warts (or AC adapters) have the advantages of being able to plug in almost anywhere indoors, no concern for having to recharge the power system, a large input voltage but at the sacrifice of portability. Batteries are for keeping good power requirements on the lower end, portability and they have the advantage of a wide selection to choose from to meet the specifications of the project but they need to be recharged. A USB power system is great for powering USB devices and because of its simplicity but it becomes troublesome when trying to power devices that don't have USB power input. DC power supplies can be configured to output the exact voltage requirements of a project but can be very expensive and they aren't practical for use as a dedicated electric power system of a project. Regardless of which system is chosen, what's most important is meeting the voltage and current requirements of each device and component so that each one functions as intended and avoids electrical damage.

3.2.7 Batteries

Seeing as some of the requirements and specifications of the UV water sanitation system are portability and being solar powered, the most practical option for powering this project would be through batteries. Further research needed to be done to determine what kind of battery is best suited for powering up the different devices and electrical components of this project. In choosing an appropriate battery for powering a project some of the important considerations (26) are:

- Budget
- Battery Capacity
- Efficiency
- Rechargeable vs Non Rechargeable
- Output power
- Size and weight
- Cycle Life and Shelf Life
- Temperature Range
- Energy Density and Power Density

Batteries are categorized as either primary or secondary batteries. Primary batteries are non-rechargeable and can produce power right away by design. Secondary batteries need to be charged before use and are rechargeable. The cycle life of a battery refers to how many times a battery can be discharged and recharged before it is unable to hold 80% of its rated charge while the shelf life is how long a battery holds its charge while not in use. The energy density is the amount of energy stored by the battery and the power density if the amount of energy the battery outputs.

Most important in selecting a battery to power a device or multiple devices is making sure that the voltage and current requirements of the devices are met so that it functions properly. If the battery provides too little power the device won't power on or won't function as intended. Likewise if the battery provides too much power and there is no voltage regulator between the battery and device then the component will overheat which can lead to permanent damage of the electrical component. The capacity of a battery is usually measured in Ah which is the quantity of amperes produced by the battery per hour. Batteries also have a voltage rating which is the voltage difference between the positive and negative terminals. Batteries can be configured in series for a larger voltage or in parallel for more capacity (more current produced in an hour) as shown in the figures below.

The current requirement of the battery is the sum of all currents being drawn from the battery.
To find the battery life we use the equation: Battery Life = (Battery Capacity)/(Load Current). The battery life will be an important consideration for the project since we need to determine how long the system can run before needing to recharge and also to ensure that we are able to sanitize the water a certain number of times per battery life.

3.2.7.1 Types of batteries

A battery's capabilities is largely determined by its chemistry and there are numerous batteries on the market with varying chemistry and forms. We researched some of the most commonly used batteries for powering a project. The capabilities of batteries hail from its composition. With numerous amounts of batteries on the market, each with different chemical compositions, it was important to understand the benefits and disadvantages of each type. The sections below discuss the most widely used batteries: Alkaline, NiMH, Lithium polymer, and Lead Acid batteries (27). Each section contains the nominal voltage, life, and other notable traits that may impact the behavior.

3.2.7.2 Alkaline batteries

Alkaline batteries are non-rechargeable batteries that have a nominal voltage of 1.5 V. They have a voltage of 1.65 volts when fully charged and a voltage of 1.4 V when fully depleted. They have a shelf life of 5 to 10 years. Alkaline batteries are cheap but the downside is that they have low power density and are non rechargeable. We quickly ruled out the possibility of using this battery seeing as one of the requirement specifications that we established was that the project be powered by a rechargeable battery.

3.2.7.3 NiMH (Nickel metal Hydride) batteries

NiMH batteries have a nominal cell voltage of 1.2. At full charge it has a voltage of 1.65 V and and at full depletion a voltage of 1.2 V. The major advantages of NiMH batteries are that they can be recharged with a fast charge time, they have high power density and they have high energy density. They also have about 800 life cycles and a shelf life of about three years. They are considered environmentally friendly because they do not contain heavy metals such as lead or mercury. NiMH batteries are moderately expensive.

3.2.7.4 Lithium polymer batteries

Lithium polymer (LiPo) batteries have a nominal voltage of 3.7 V. They are rechargeable and recharge quickly. They have a cycle life of more than 500 and a long shelf life but it is comparatively expensive, even more expensive than lithium ion batteries - they have a higher cost to energy ratio than Lithium Ion batteries and a lower capacity than Lithium Ion batteries. They have a high energy density but not quite as high as that of the Lithium Ion battery. These batteries are light and can be purchased in very compact form. LiPo batteries are also environmentally friendly. This battery's small size, fast recharge time and good energy density make it viable for use in the PUVC.

3.2.7.5 Lithium ion batteries

Lithium ion batteries have a nominal voltage of 3.6 V and are relatively expensive but they have very high power density and energy density. They are rechargeable, generally have a cycle life of a few thousand and a shelf life of about 10 to 20 years. Lithium ion batteries are widely used in everyday devices such as laptops, smart phones and electric cars. The downside of lithium ion batteries is its high cost. Lithium ion batteries require protection circuits to ensure safe operation and that it meets its full cycle life. The protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. The high energy and power density of these batteries make them a suitable candidate for powering the PUVC.

3.2.7.6 Lead acid batteries

Lead acid batteries are rechargeable and are quite large compared to other batteries. They have a nominal voltage of 2 V per cell. They have a very long charge time and can be easily damaged irreversibly if they are left in the discharged state due to sulfation. Lead acid batteries should not be completely discharged as this will shorten the battery's cycle life. They have low energy density and are bulky but have a low self discharge and are inexpensive. These batteries are not suitable for portable devices due to the low energy density and large size so it was quickly ruled out as a contender for the battery that powers the PUVC.

3.2.8 DC to DC converters

DC to DC devices are electronic devices that take an input DC voltage from a voltage source and convert it to another voltage level at output. Depending on the method of conversion DC to DC converters are classified as switching converters or linear converters. Linear DC converters utilize linear electronic components such as resistors and can only be used as buck converterters. They have less frequency noise than switching converters but are not very efficient as they generate a lot of wasted power in the form of heat. Switching regulators are very energy efficient but are more complicated to design. They utilize electronic storage devices which store energy in the magnetic field such as inductors and electronic storage devices which store energy in the electrical field such as capacitors. DC to DC converters can be classified as step-up converters (also called boost converters) and step-down converters (also called buck converters). Switching regulators are generally far superior to linear converters as they have a much higher efficiency.

3.2.9 Battery charger circuit

The battery charger circuit controls the power supplied from an AC source such as a wall outlet and uses it to safely charge batteries. In order for a battery to be optimally charged it requires a constant voltage, constant current and a mechanism to cut off the battery once the battery is fully charged.

Three stage battery circuits are commonly used as battery chargers and consist of three stages - bulk stage, absorption stage and float stage. 80% of the battery is charged in the bulk stage where a constant current of 10-25% of the Ah rating is provided. Although the battery can be charged a percentage greater than 25% of the Ah capacity, charging the battery at 25% or lower of its aH quantity preserves the battery life. The remaining 20% of the battery is charged in the absorption stage where the charger maintains a steady voltage while the current supplied to the battery decreases. This is to prevent the battery from overheating. Finally, in the float stage is the stage where the charger reduces the current to a trickle and the battery is being charged constantly to maintain a state of 100% charge.

3.2.10 Solar Charge controllers

Charge controllers are electronic devices that regulate the voltage and current going into a battery from a charging source. The purpose of these devices are to prevent overcharging of the battery which can damage and shorten the battery's cycle life. Charge controllers are essential in using solar panels to charge batteries because they need to regulate the voltage being supplied to the battery.

In spite of the fact that most PV solar panels are built to produce a nominal voltage of 12 V, in practice they usually output a voltage closer to 17 volts. This higher than nominal voltage is to accommodate variation in the sunlight available to the PV solar panel when the sun isn't directly overhead. Charge controllers also often control other parameters such as the charge rate of a battery based on the manufacturer's recommendation for optimum cycle life of the battery. Additionally, they are responsible for managing how much power is drained from the battery by the connected electrical devices and will disconnect these electrical devices in the event that the battery is being over discharged.

Charge controllers are also needed to prevent reverse currents from flowing into the solar panel. This can happen at night for example when the solar panel has a lower potential than the battery as current flows from a high potential to a low potential. Some of the common types of charge controllers are MPPT (Maximum Power Point Tracking) controllers, PWM (Pulse Width Modulation) controllers, simple stage controllers and series regulators.

3.2.10.1 MPPT (Maximum Power Point Tracking) controllers

MPPT controllers optimize the match between the power being output from the solar panel and the power being input into the batteries. Due to the fact that power produced by the solar cell is dependent on variables such as temperature and solar radiation, there is a need for adjusting the operation of the solar cell to work at the maximum power point or most efficient voltage. MPPT controllers work by monitoring the output of the solar panel and the voltage of the battery and then adjusting the output for the most efficient combination of voltage and current.MPPT controllers are also able to supply power directly to a DC load connected to the battery. MPPT controllers are able to produce 10-30% more power than PWM controllers but are more expensive than PWM controllers.

3.2.10.2 PWM (Pulse Width Modulation) controllers

PWM controllers work by supplying power in pulses from the solar panel to the battery. The length of the pulses (duty cycle) and the pulse time of the pulses is based on a switching mechanism built into the circuit of the PWM controller. This mechanism regulates the amount of power flowing into the battery. The amount of power being supplied to the battery from the solar panel is dependent on the battery charge level. A lower battery level results in higher pulse length and pulse times. Likewise when the battery is fully charged and it doesn not require as much power, the PWM controller will lower the pulse lengths and pulse time of the solar output.
Although PWM controllers are not as efficient as MPPT controllers they are a good low cost option for smaller systems where maximum efficiency isn't a high priority.

3.2.10.3 Simple stage controllers / Shunt regulator

Simple stage controllers or shunt regulators are linear regulators that work by shorting the solar panel once the desired voltage of the battery is met. They operate by utilizing a simple switching mechanism or voltage diode which causes current to flow to the ground instead of to the load. Shunt regulators are generally only used for small currents and low voltage applications that have a fixed range.

3.3 Strategic Components and Parts Selection

To enable ourselves to in fact be able to proceed through senior design two with as much ease in building as possible we ventured to attempt to catalog, compare, and purchase as many key components as we were able to. Due to the pandemic many companies were more difficult to come into contact with, get descriptive information from and even with purchase from as lead times on almost all essential electronics have risen. With these challenges in mind we prioritized first understanding exactly what we needed through extensive research and now in the section define and select the key components we believe will make our project successful.

3.3.1 UV LED selection

As discussed earlier UV LED and lamp selection was a crucial process for our project. Many iterations of the design with many different configurations of LED's and lamps were evaluated before a final design was put forth. For the PUVC to be effective we estimated the system would require power above 50 mW to kill most waterborne pathogens. The PUVC will employ an array of diodes within the high power LED ring and also within the sanitation tank to provide efficient cleaning of the water. There were also many considerations to make when purchasing our diodes. The primary ones being emission wavelength, bandwidth, output power range, temperature needed for operation and lifetime of the diode. Shown below in table 3 is a comparison of these key characteristics for five diodes that we have selected to be possible diodes for the PUVC prototype. These diodes all have their own unique properties but to flush out what would be the best diode for the PUVC we had to fall back to our research. As mentioned in section 3 the germicidal effects of UV are greatest in the range of 100-400 nm, because of this we attempted to find UV diodes within this range(14, Kowalski). UV is difficult to produce in most diodes as a complicated chemical mix of semiconductors materials is needed to produce a diode capable of emitting UV. Not only this but to achieve the lower wavelength needed to produce UV capable of sanitation the device must have a design involving semiconductor materials with an energy band gap at the right energy to be harnessed into an ionizing photon. Power was also a major consideration when thinking about the diode employed for the PUVC. The diode had to deliver enough power so that the coliform was effectively negated but also be able to have a long lifetime. Having a long lifetime allows for the PUVC to have added value based on the price, a very important factor if the device is attempting to be used by those communities without clean water. On top of these demands the energy requirements of the LED had to be manageable so that the battery will not become depleted immediately. Another key quality of the diodes that should be mentioned even though it was left off the chart was that the diode for the PUVC must be modulable in its power demands. Due to the fact that we would like the PUVC to be able to run in different power modes to improve efficiency, we chose to only evaluate diodes that were able to run in distinct power modes and did not require complicated additional electronics to operate.Not only must we consider the LED's functional data but also the cost it would take to have the diodes that we need. We will need a total of 14 diodes for our current final design and without these being cost effective the PUVC will suffer greatly in its marketability. On top of this due to the pandemic there has been a large change in the lead time of several electronics. Due to this extensive pre planning must be done to ensure parts will be available for when they are implemented in the final design.

Table 3: UV LED comparison Table

UV LED	*Emission wavelength*	*Emission Spectral Half-width*	*Output Power Range*	*Operational Temperature*	*Lifetime*	*Emission Angle*
ILT E275-3 LED	275-285 nm	10-12 nm	3-6 mW	25 ℃	10,000 hours	120-130 °
Mouser CO3-UV	365-405 nm	10-15 nm	126 mW - 1.3 W	25 ℃	1,000 hours	130 °
ILT E-275-10 LED	270-280 nm	10-12 nm	8 - 18 mW	25 ℃	10,000 hours	130 °
SVC UVC LED	265-310 nm	15-20 nm	.3-2.5 mW	25 ℃	2,000 hours	140 °
Banggood UVC SMD LED	275 nm	10-12 nm	3-5 mW	25 ℃	10,000 hours	120 °

Shown below in table 4 are the lead times we were able to obtain from the various suppliers and as can be seen for most suppliers the lead times are far longer than usual. Especially for those diodes coming from china that are often the cheapest to purchase. To overcome this the team attempted to order early diodes for testing but long lead time and unresponsive suppliers left the team with little response other than to go to local suppliers. As can be seen in the cost table the cost for UV diodes that are made to produce germicidal UV can range dramatically in price. This price change can be largely attributed to the different materials used for each diode and the diodes we selected range from cheap to expensive to implement. The main trade off we could derive from the cost of the diodes was that as the power increased so did the cost of the diode. This simple realization forced the team to rethink the PUVC design and implement a design capable of harnessing lower power to perform effective sanitation.

Table 4 : Comparison of LED cost and supplier

UV LED	***Cost***	***Cost for 10 units***	***Lead Time***	***Supplier and location***
ILT E275-3 LED	$ 13.00	$ 130.00	7-20 Days	International Lighting Technologies USA
Mouser CO3-UV	$ 6.53	$ 59.10	14-21 Days	Mouser Electronics USA
ILT E-275-10	$ 32.00	$ 320.00	7-20 Days	International Light Technologies, USA
SVC UVC LED	$ 40.41	$ 391.30	20-35 Days	EBAY China
Banggood UVC SMD	$ 5.09	$ 50.90	10 -15 Days	Banggood China

As stated earlier we had first envisioned the project using a UV lamp as the ultraviolet source for our project. UV lamps provide a high watt output but often require high voltage and current to run. The large size of UV lamps also could potentially greatly limit their application within our project. Due to our requirements of optical complexity as well it proved ineffective to use any UV lamps in our project as the only source for UV. LEDs offered a novel and challenging solution to the PUVCs problems while also allowing for a more portable and durable potential design.

3.3.1.1 Final LED Selection

The International Light Technologies (ILT) E-275-3 is the UV diode we are planning to use in the PUVC. The E-275-3 LED is a diode capable of operating with a forward voltage of 5-7 V and a current of up to 90-100 mA depending on the LED mounting. We have chosen the E-275 because it best fits all of our parameters while also providing enough power to provide sanitation. To operate the E-275 we will connect the diodes through their cathodes and anodes to our power board and mount them within the ring and the sanitation chamber. The E-275 requires constant current to operate and requires a 5-7 volt voltage for power. The diodes work best at 25 °C and are operational at temperatures between 10-50 °C, and in the manual it is stated for optimum operation the LED should be connected to a copper based heat sink with dimensions near 1.6mm thick and 20 mm wide. Due to our device being water oriented we expect the temperature to stay easily within this range. We will also take advantage of the water and design housing for the LEDs that are cooled as the system runs through the flow of the water through the unit. This will allow for the heat sink to be brought down in size. This is due to the fact that with water more temperature is removed from the heat sink through the thermal effects of water flowing through the piece than could be achieved through simple thermal dissipation in a plate. The E-275-3 can also operate at three distinct power levels depending on the current and voltage fed to the diode. These powers and accompanying current values from the manufacturer are as follows, 3 mW output at 6 V with 20mA current, 4 mW output at 6 V with 30 mA current and 6 mW output at 6 V with 50 mA current. At all these current values the diode produces a wavelength of 270-280 nm. This wavelength range optimally fits the range we needed based on the research done into removing waterborne pathogens. Shown below in figure 9 is the UV LED we are currently planning to use as well as a verison of the LED mounted already to a board. As can be seen the diode offers a simple connection and we expected to be able to mount LED with relative ease inside the PUVC. Additional design considerations will have to be made to ensure the diodes are kept free of water and are properly temperature controlled as the powers are modulated. The E-275 is able to stay operational at a humidity percentage under 65% and it is recommended to operate the LED with it being hermetically sealed. To account for this design modifications will have to be made to ensure the enclosure for the LEDs within the high power ring and sanitation tank are properly sealed to avoid excess humidity.

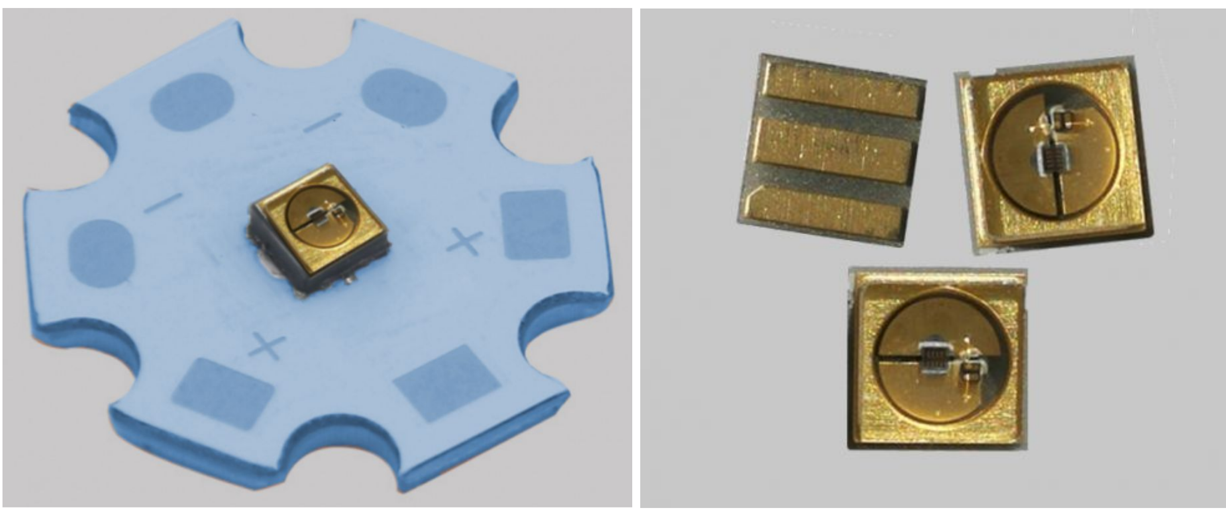

Figure 9: UV LED E275-3, and E275-3 mounted on board as sold from distributor (Reprinted with permission from ILT)

To design an appropriate rigging system and optical system to focus the emissions of the LED the output characteristics of the E-275 must be known. Since we are aiming the LED to be applicable in water at a range and power density needed for pathogen sanitation, several output characteristics had to be established first. These characteristics would also have to be characterized through testing to ensure that the PUVC would indeed be operational using the E-275. Further information regarding the testing of the PUVC can be found in section 8. To design the PUVC with appropriate optics we evaluated the application of the LED given its 120-130 degree divergence angle and 3-6 mW output power. We decided that we would need a lens system to collimate the light and then re-disperse it through the water so that a greater energy density can be achieved. The planning for these optics can be found in the design section under section 5. Shown in the graphs below in figure 10 is the output spectrum from the factory of the E-275 diode. These output characteristics as stated before allow us to better design our PUVC so that we get the greatest germicidal effects.

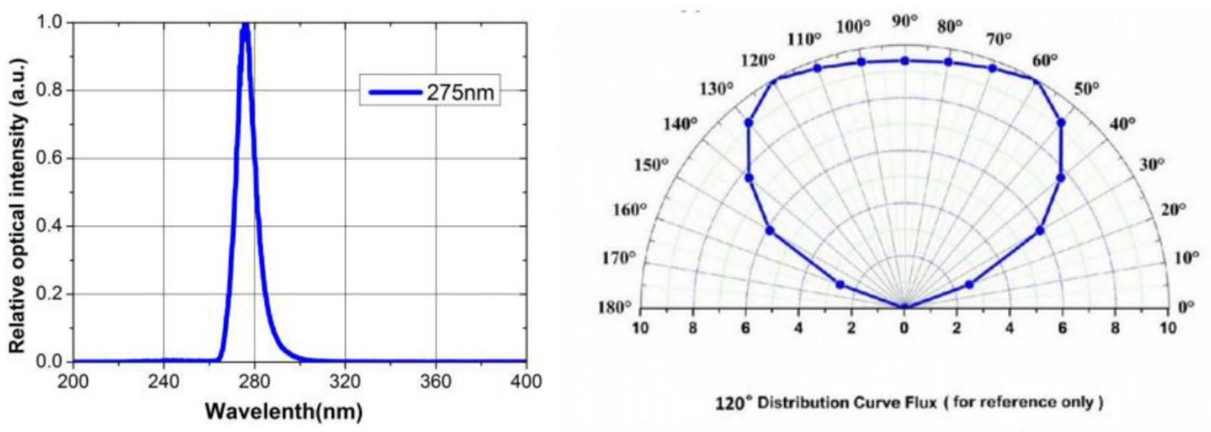

Figure 10: Factory LED output wavelength (left) and distribution curve flux(right) for reference (Reprinted with permission from ILT)

In summation the purchase of the E-275 as our prototype LED was the combination of a litany of factors. The LED offers the best option for our germicidal effects as well at a moderate price point that allows for integration into the PUVC. Not only this but as the team attempted to get verification on information for the diodes, or even just the base characteristics of the output we were met with stonewalls. The only company to actually respond was ILT and because of their technical support we decided it would be best to spend more on the diode to maximize the amount of assistance we could get in case the diode did not work or we had issues with implementation. We were also able to establish a communication line with ILT further encouraging us to pursue using the E-275 in our design. We would like the reader to keep in mind though that as this paper is primarily focused on the creation of a prototype and the simple proving of an idea we chose to go with the option that gave us the greatest chances for success instead of the cheapest option. In the future once the design is more refined and the team's understanding of the germicidal effects of UV increases we will be better able to assess where costs can be lowered so that the product could eventually become marketable. There is also plenty of room within the modular design that in the future a different array of LEDs could be implemented as well as even phase out the use of the E-275 if a more efficient design is put forward.

3.3.1.2 Safety and Environmental Considerations for use of E275-3

To ensure proper safety of the team and of the end users of the PUVC, proper safety precautions must be taken when endeavouring to create the prototype. As was mentioned in the earlier research section 3, UVC is ionizing therefore it is a higher energy wavelength capable of damaging DNA and RNA(4,Buonanno). The same power we are harnessing to power the sanitation process could also create a direct danger to the user and the team when prototyping and when operating the device. The PUVC will be an enclosed unit therefore there is no risk for exposure to the LEDs while the device is operational provided there is no tampering with the device to allow it to run as such. We as a team are putting effort forward to create a design that allows for safety to be a top priority while maintaining a modular design. This has created several design constraints to ensure that the diodes are off whenever an emission component is removed or the sanitation tank is open. Our solution will be to instill software and electronic backups that will automatically switch off the diodes if any damage could occur. The E275-3 does have several environmental advantages that we see though that allowed us to feel justified in proceeding with the purchase of these diodes. The primary advantage is that this diode produces no ozone in comparison to UV lamps which when operated produce wavelength within the vacuum UV range of 100-185 nm. The production of these vacuum wavelengths in turn causes a photolysis effect on the oxygen molecules present in the water. The incoming photon disrupts the molecule and creates a valent oxygen atom that then binds to produce the ozone O3(22,Voronov). While ozone is harmless at lower levels, if levels become high enough water can be contaminated to the point where consumption could cause sickness.This removal of ozone producing opto-electronics gives us greater confidence that through that process of cleaning the water of pathogens we will not impact the potability of the water. In summation the E275-3 as fit in our current design offers other environmental benefits and drawbacks but for PUVC offers the best solution to our needs of a UVC diode capable of sanitizing water.

3.3.2 UV Lamp Selection

When evaluating the UV lamp we had several considerations to make. The most important of those was having a lamp that would fit effectively within the processing tank while also providing enough power to perform UVGI when being used as a backup sanitizer. We chose to evaluate the lamps based on several factors such as emission wavelength, output power, ozone production, cost, lead time and lifetime to name the most important metrics. The table shown in table 5 shows some of the characteristics of the lamps that we evaluated for use. As can be seen there is great variability within these lamps in the wavelength that they produce and the powers. This is because of the different material makeups, pressures used, and photon generation methods used. We decided to narrow our focus to only lamps that were able to fit inside a gatorade 10 gallon as it mimicked the size we aimed for the PUVC as well as looked for lamps that produced little to no ozone if possible. We chose to attempt to find lamps that produced as little ozone as possible to create a safer end product and eliminate any possibility to cause the water to absorb excess ozone. This involved us vetting our suppliers of UV lamps to only those capable of producing lamps that were low in ozone production and had medium to low gas pressures. Though we were unable to find any lamps within our price range and that were not composed of a device with accompanying electronics to remove the ozone we were able to find many extremely low ozone production lamps commercially available. We were able to verify with several suppliers that the lamps when used in the way that we seek would create virtually zero ozone as the lamp will be on for a couple of seconds at a time. With this in mind we then decided on the five lamps shown in table 5 on the next page. To decide which was best we again referred back to our earlier research section and focused on lamps able to produce wavelengths and power in the germicidal regime. We also ventured to find a UV lamp that also had a power supply that was integratable into a 12 V system without causing many extra electronics to be used to regulate the power. It soon became apparent that to produce light from these lamps an

AC current would be needed. Further discussion of this can be found in DC to AC converter section 5. For the UV lamp we did a similar cost analysis and lead time analysis to understand which lamp would allow for the project to be completed in a timely manner. As we found with the LEDs there was also great difficulty in getting into contact with manufacturers and were greatly delayed in being able to get essential information on the lamps. The long lead times again forced a large effort by the team to catalog and understand what times we ordered and when testing could be done. Testing plans and procedures can be found in section 8 where more detailed assessments were made on how to test and implement the lamp into the PUVC. Lifetime of the lamp was also a major consideration of our team due to the fact that we would like the device to be usable for a large amount of total water and still ensure effective cleaning. Running the lamps for a shorter duration of time will increase the potential life time of the UV lamp but the team still assessed that the lamps would need at least 5,000 hours or more to be useful. Given this amount of usable hours we estimate that when using the lamp as the primary sanitation source given testing has warranted it the PUVC should be able to process above 1 million gallons. While this is a bold claim, given our current understanding if the PUVC is properly operated sanitation could be performed for an extremely high volume of water over the duration of a year. This perfectly fits with our motivation and initial design goals and would allow the PUVC to have true application in communities impacted by water contamination.

Table 5: UV Lamp comparison Table

UV Lamp	*Emission wavelength*	*Output Power Range*	*Cost*	*Lead Time*	*Lifetime*
GermGuardian - LB1000 UV-C	200-280 nm	3.5 Watts	$ 16.99	10 -15 Days	5,000 Hours
HBO Ultra High Voltage UVC Bulb	200-700 nm	100 Watts	$ 91.99	10-21 Days	5,000-8,000 Hours
Ster-L-Ray GPH436T5L	200-700 nm	48 Watts 13 W @ 254 nm	$ 89.00	7-10 Days	13,000 Hours
Ster-L-Ray G18T5L-U	200-700 nm	18.4 Watts 5.8 W @ 254 nm	$ 115.00	7-10 Days	10,000 Hours
G25T8 25-Watt Germicidal Tube	200-700 nm	52 Watts	$50.00	14-21 Days	8,000 hours

In conclusion when purchasing UV lamps the team had many of the same considerations that were assessed when choosing the LED. We evaluated not only the effectiveness of the lamp in terms of its ability to inactive pathogens but also its long term implications in cost, environment and workable lifetime. The team also considered which lamp would be most integratable into the overall electric design and allowed for the most efficient power modulation for use in sanitation. Discussed in the following section 3.3.2.1 will be a detailed description of the UVC lamp chosen for the design and its accompanying characteristics.

3.3.2.1 UV Lamp Final Design Selection

The final Lamp that has been chosen for now is the STER-L-RAY G18T5L-U, or SLRU for short. The reason the SLRU was chosen for the PUVC is because it is the most compact of all the UV lamps and provides the highest ratio of size to power. The SLRU is also made of quartz which allows for more of the energy produced within the lamp to actually be output into the system as absorption and reflection losses are reduced. The SLRU is going to be employed within the sanitation tank as an assurative measure that if the LEDs are not powerful enough to sanitize the target pathogens. If the analysis verifies that coliforms were detected in water then the lamp can be turned on as an extremely high power source for the relative volume ensuring any UV susceptible pathogens are destroyed. The SLRU is a broadband source as it is a medium pressure mercury lamp therefore it will produce wavelengths outside of the effective germicidal range, but much of the power will still be emitting in the UVC range. The SLRU operates as a self ballasted lamp as well offering a more simple integration then exterior ballasted lamps. Although due to this the pulsing of the lamp it will become more difficult to integrate. There will have to be a time delay in the electronic and software systems to allow for the lamp to cool down and be reignitable. If properly instituted and with the aid of water cooling the lamp the device should still be able to operate at a high volume output. In addition to this the SLRU is also able to run for an estimated 10,000 hours giving the PUVC a very long lifetime and added durability. The SLRU is operated through an AC current as well which will force a design of a voltage converter to ensure the lamp is properly alternated for proper function.

The lamp overall produces a power of 18.4 watts broadband but the majority of the power is not usable specifically for UVGI. This is not a problem though as we were able to find the relative power produced from the lamp at 254 nm which is within the UVC range. Within this range the SLRU is able to produce 5.8 watts of power, this power level far exceeds the amount we need for the volume of water we can contain in the PUVC and therefore provides an excellent solution to more rapid processing speeds. The SLRU will allow for the PUVC to perform cleaning at a very fast pace while also allowing for the production of broadband UV. This broader spectrum of UV will ensure that if the initial UVC LED sterilization is not successful a broader spectrum can be employed to neutralize other pathogens with different absorption characteristics. There will also be no additional optics needed to redisperse the output of the lamp as it will already have such a large output that no matter where it is placed inside the sanitation tank it will provide a high enough UV dose. The only additional parts needed for the SLRU are an AC converter and a protective covering mount so that it is not damaged by the water flow. A stock image of the SLRU that will be used in our product is shown below in figure 11.

Figure 11: Stock image of STER-L-RAY U shape lamp intended for use in PUVC (Reprinted with permission from ILT)

In conclusion the SLRU was selected by our team because it was the most energy efficient, compact, and powerful lamp that we could find that was within a reasonable price range for our team to personally fund. A more detailed design incorporating the SLRU inside the sanitation tank can be found in section 5.

3.3.2.2 Safety and Environmental Considerations for use of G18T5L-U

UV lamps have much of the same environmental and safety considerations as the UVC LEDs. The SLRU although due to it being a mercury lamp when at full operation has the potential to produce excess ozone that could contaminate the water. To avoid this the SLRU can be turned off before a large amount of ozone would be able to accumulate.This would take an extremely long time with the lamp turned to maximum output thought to produce any dangerous amount of ozone. As discussed earlier, if the lamp is suddenly turned off time is needed for that lamp to cool down and recondense the argon and mercury so that an initial ignition can occur again. Due to this design modifications will have to be made but the team is confident that the lamp will operate effectively when operated in a pulsed mode and allow enough time to cool down. Additionally the team will attempt to use the water surrounding the lamp to cool it allowing condensation to occur more rapidly. The safety hazard of the SLRU while similar to the E275 must be treated with more care. UVC exposure from the lamp over time could cause damage to the skin inducing melanomas (16). The SLRU is capable of producing potentially dangerous amounts of UVC radiation if activated without the presence of water and therefore precautions will have to be taken to prevent the SLRU from being operated in open air. To ensure operation when the device is turned off the PUVC will employ a small monitoring camera to be able to view inside the tank and show the user whether the lamp and LEDs are operational or not. Once it is registered that the LEDs or lamp is indeed operational then the sanitation process will begin and the tank will be locked from opening. In conclusion the SLRU will offer much the same environmental constraints that the LEDs did but our team will ensure the system provides ample protection to the user.

3.3.3 Optics and Protective Covers

Several other considerations must be made when selecting optics and protective coverings.

To ensure that the UV light is properly dispersed, the coliform test is visible to the camera and ensure there is not too much additive loss several optics would have to tested and then be employed in our system. The team took great care to ensure that the optics were cost effective while also still providing the PUVC with the proper dispersive properties for our application. This section will discuss the major factors we assessed when choosing our lens materials and why we purchased the optics that we did. The coverings and lenses of the optics in place not only must be considered for their dispersive properties but also for power loss that could occur through transmission. Several other parameters must also be assessed to ensure the power delivery is appropriate such as how the material reacts with water and if its structure could be vulnerable to higher intensity UV rays. A more detailed explanation of our purchasing process of our lenses is shown below. In conclusion the team had several parameters to explore when considering the optical setup of the device to ensure the PUVC had the optimal UVC distribution, power, absorptive properties, and provided protection from any water.

3.3.3.1 Lense Selection

To ensure that the UV light from the LED's inside the PUVC are properly dispersed and not absorbed the correct lenses must be chosen. On top of this there has been considerable thought put into how to redisperse the light for the PUVC so that a greater UV dose can be achieved. This forced the team to consider not only material composition but also the variety of curvatures and shape profiles that would be available with each material. The first lens parameter we decided on was the lens material. The material options that we compared were Calcium Fluoride, Barium Fluoride, UV Fused Silica and Magnesium Fluoride. Once we had decided which materials were available to us to be able to emit and focus UV we then set about comparing the various characteristics of each material type. Shown on the next page in table 6 is a comparison of the transmission wavelength range, lens shapes available, index of refraction and the Abbe number of each material

Table 6: Comparison of Lense Material Characteristics

Material Type	***Wavelength***	***Lens Shapes***	***Index of Refraction (at D line)***	***Abbe Number***
Barium Fluoride	200 nm - 13 µm	Plano-convex, windows, wire grid polarizers	1.468	81.78
UV Fused Silica	200 nm - 2 µm	All Available Forms	1.458	67. 82
Calcium Fluoride	200 nm - 11 µm	Lenses, prisms, windows, beamsplitters and polarizers	1.428	95.31
Magnesium Fluoride	200 nm - 6 µm	Plano-convex,	1.390	106.22

Upon reviewing the materials above we decided to use UV fused silica as our lense material because it is the most cost effective, allows for the most lense options, and fits in our ideal transmission range. The silica lenses our team will focus on will be a set of two or three pending further testing on collimation of LED light shown in section 8. A more detailed explanation of our final lense is shown below in section 3.3.3.2. Once we had decided upon the use of UV fused silica as our material we then established the price points of reputable vendors, sizes of lenses available and the lead times of each company. Shown below in table 7 is a comparison of the sizes of lenses available, cost and what the potential lead time for purchasing would be from these distributors.

Table 7 : Comparison of Company Characteristics for UV fused Silica Plano Convex Lens

Company	***Price***	***Sizes***	***Lead Time***
Thorlabs	$65 - $248	2 mm - 75 mm	7 - 30 Days
Edmund Optics	$94 - $238	5 mm - 50 mm	14 - 30 Days
Surplus Optics	$30 - $128	13 mm - 200 mm	7 - 14 Days

In conclusion after weighing which lens material was the best for our designs as well as several manufacturer statistics the PUVC team has decided to use UV fused silica lenses. UV fused silica lenses provide the best solution to all of our needs and would be the most cost effective to implement. A detailed description of the lenses specifically selected and their characteristics can be found in the following sections.

3.3.3.2 Final Lense Selection

The final lenses we have selected for the project are UV fused silica lenses from Thorlabs and Surplus Optics. These lenses are the most affordable, variable, and have a good range of lead times to be feasible within our project. We have two lense companies selected as we would like to be able to test which is most applicable for a long term product. The lenses that we would like to test for our application are biconvex, plano-convex, and biconcave lenses. These lenses will allow us to collimate the LED UV emission and then also redisperse it in a tighter distribution so that a greater dose of UVC can be delivered. To accomplish this the lens design shown in section 5 will seek to collimate one or two LEDs in close proximity and then redistribute the light patter with a lens matrix. The team is still testing whether a collimating lens is in fact needed or if a simpler matrix can be used but due to testing restraints detailed in section 8 we have been unable to assess the best optics to use. Shown below in table 8 is a potential cost estimate that we have prepared for the PUVC. In it are the two distributors as well as the cost of the expected components, their sizes and the potential total cost of an optical setup composed of these elements.

Table 8: Cost Analysis of Lens System

Company	***Bi-Convex Cost***	***Bi-Concave Cost***	***Plano-Convex Cost***	***Total Estimated Cost of system***
Thorlabs	$ 108.21	$ 92.52	$ 90.90	$ 508.05
Surplus Optics	$ 26.25	$ 14.25	$ 30	$ 121.20

Once the costs of the system in total were analyzed the team decided to start with the surplus optics lenses. This would put the total estimated cost of the lens setup to be near $121.20. The team is not 100% percent confident though, of the quality of the optics therefore we have still contacted thorlabs to have lenses ready for us if they are needed. Once these optics the team will proceed with testing and evaluate if the method needs to be changed.

During the process of receiving the lenses there was a much longer delay than expected. On top of this the original supplier of our lenses was unable to fulfill our order in the end and did not notify the team until the supposed delivery day. This forced the team to reorder more expensive lenses from a reputable dealer to ensure the progress of the prototype. In the end the team bought 1 biconvex lens from Edmund optics, 1 plano convex and 1plano concave lens from Eksma optics. The lenses total cost with delivery was near $500 dollars. These were by far the most expensive components of the device. Once the lenses were acquired they were then tested for power loss as shown in section 8.

3.3.3.3 Final LED Protective Panel Selection

For any and all covering panels for the LED arrays several considerations similar to the lens selection process would have to be made. These protective panels will be flat planes containing no surface curvature therefore redirection to a large degree can be ignored as long as the LED stays perpendicular to the panel. When selecting a covering for the UVC lamp as well the curvature can for the most part be ignored. Due to the very high output of the lamp and because it requires no collimation or redirection there will be no need to consider curvature and loss as they will not severely detract from the lamps effectiveness. The panels for the LEDS will also not be bent as there is no need to do so within the chosen design shown in section 5.There will be loss on the UVC power due to the panel being in place but our supplier has stated to the team that we can expect a transmission percentage near 92% which for the price point is far greater than anything we have been able to find on the market. Other vendors at lower price points often had manufacturing only in China which would lead to much longer lead times and potential shipping problems. Not only this but TOPAS advanced polymers also use novel techniques for creation of their silica offering purity levels that allow for even greater UV transparency. The team again thought it best to again go with a partially American based company not only for the faster lead time but also because the user support has so far to our experience been much greater in the United States. The panels that we will be choosing to protect our LEDs in the high power initial UV array and within the sanitation chamber will be UV fused silica panels of varying thicknesses custom made from TOPAS advanced polymers. The thickness of these panels will vary from 3-5 mm depending on how TOPAS is able to settle the silica and what ends up being most effective in our design. The exact specifications of each panel size and placement can be found in section 5 optical designs. These coverings will allow the LEDs within the array to come very close to the water therefore they must be properly protective and resistant to wear so that it does not cause damage down the line. Due to cost constraints as well the team tried to relegate our design and incorporation of the fused silica in a manner that would not require expensive machining.The team also assessed where costs could be reduced and found that a simplified optical design allowed for great cost reduction. There also stands to be many ways in which our design could alternatively be used in the PUVC such as changing the arrangement of LEDs, lamps or incorporating curved coverings within the unit. The team would like the reader to keep in mind the use of UV fused silica could change as the PUVC evolve as more testing is done to see the effect of using silica longer term in a water based system. In conclusion UV fused silica panels purchased and machined by TOPAS advanced polymers and a sheath will be used in the PUVC final design. This is because they offer the greatest mix between transparency to UV and price that would allow us to effectively create a prototype PUVC.

3.3.3.4 Cost Constraints for Optics Purchasing

Cost was a serious issue when selecting optics for the PUVC. Due to the large expense of optics our team was extremely limited. In addition to this project being completely student funded there is also the COVID epidemic causing additional financial strain on the team. Due to this the team had to greatly weigh whether a purchase of a lens was truly going to work within the PUVC. To avoid needless spending of essential funds the purchase of lenses were delayed while cost analysis was done. Also due to additional constraints from lack of communicational availability due to COVID the team was unable to get a good amount of consultation on which lenses would in fact perform the best. The cost was also prohibitive because of our original design constraint of wanting the overall cost to come in under $1500. At first the team ventured to collimate the UVC light before it entered the lens matrix but due to the average collimating lens costing near $300 it was not necessarily an option considering the funding for the project. There were many attempts to receive discounts in exchange for inclusion into the report or accreditoon but these attempts were turned down due to newly revised pandemic spending plans.

3.3.4 Solar Panel Selection

The major modern solar panel types are the monocrystalline, polycrystalline and thin-film solar panels. Monocrystalline solar panels use single crystal silicon which gives electrons activated by photons more room to move. Polycrystalline solar panels use fragments of silicon and generally have lower efficiency than the monocrystalline panels. Thin-film solar panels are generally made from a cadmium telluride (CdTe), amorphous silicon (a-Si) or Copper Indium Gallium Selenide

(CIGS) middle layer between two conducting layers and have a thin glass protection top layer. The most important properties of these solar panel types which were factored in selecting a solar panel for the PUVC are listed and compared in table 9 below (23).

Table 9: Comparison of characteristics of main solar panel types

Characteristics	Monocrystalline	Polycrystalline	Thin-film
Efficiency	Highest Efficiency	Moderate Efficiency	Lowest Efficiency
Cost	Most Expensive	Moderately Expensive	Cheapest
Longevity	High Longevity	High Longevity	Lower longevity

Based on the characteristics outlined in table 9 above, we decided to focus on selecting either a monocrystalline or polycrystalline solar panel. The major decision to be made between the two is whether higher performance or lower cost is more important. It was calculated that 25 W would be optimal for powering the PUVC's electronic components. 12 V is also desired to match the 12 V battery. The size of the solar panel will also be a factor of consideration since we want to maintain some level of portability of the PUVC. It was ultimately decided that the Newpowa 30 Watts 12 Volts Monocrystalline Solar Panel would be selected as the solar panel to power the PUVC. This solar panel was chosen because it has a 30 W power rating which is sufficient for the power requirements of the PUVC.

3.3.4.1 Newpowa 30 Watts 12 Volts Monocrystalline Solar Panel

This solar panel is a 30 W high efficiency panel with dimensions of 21.54 x 13.39 x 1.10 inch. These dimensions fit within the maximum solar panel length of 3 feet listed in the engineering requirement specifications. At maximum power point this monocrystalline solar panel has a voltage of 17V and a current of 1.76 A. This output current of 1.76 is enough to achieve a charge rate of 0.1 C for the 12Ah battery we have selected. It comes with an attached 3 foot bare ended red and black wire. No datasheets of this solar panel could be found but it was considered because it was one of the top featured panels on Amazon. This solar panel is listed at a price of $40.97. It is not too expensive and it would be difficult to find a cheaper solar panel at a 30 W power rating.

3.3.4.2 TP-solar 30W Portable Foldable Solar Panel Battery Charger Kit

One of the other solar panels considered for this project was the TP-solar 30W Portable Foldable Solar Panel. The attractive feature of this panel which made it a contender for our choice of solar panel is its portability. This solar panel is a four piece foldable panel with dimensions of 33.3 x 11.1 inch when unfolded and 11.1 x 7.6 x 1.5 inch when folded. The unfolded design is shown in figure x below The compact folded size would make it very easy to store and it upholds the feature of portability of the system. This solar panel is fully laminated which makes it waterproof and adds to its durability. It has an efficiency of 22 % and costs $69.99 which is fairly expensive. Shown below in figure 12 is a portable foldable solar panel.

Figure 12: TP-solar 30W Portable Foldable Solar Panel
(Permission to reprint given by Mobisun)

3.3.4.3 Potential Environmental Impact from PV Solar Panel Choice

The environmental impact associated with PV systems are the following, the toxic and harmful materials used in the production of PV cells, the energy required to produce the photovoltaic systems, and what happens to the PV systems at the end of their lifetime period. Also, some of the common harmful chemicals involved in crystalline photovoltaic manufacture are: Sulphur Hexafluoride used to clean the reactor used in silicon production and if the product escaped it would be a very powerful greenhouse gas. Also, it can react with silicon to create a variety of other compounds. The main component of photovoltaic cells is silicon. Silicon is not a harmful material, but parts of the manufacturing process involve toxic chemicals and they need to be carefully controlled and regulated to prevent environmental damage. Crystalline silicon is made via silane gas. Moreover, the production results in waste silicon tetrachloride which is toxic. Silane gas has the potential to cause harm, also lead, aluminum and silver in the electronics. The use of lead based solder would lead to pollution problems. With the exclusion of amorphous silicon, most commercially established photovoltaics technologies use toxic heavy metals. CIGS often uses a CdS buffer layer, and the semiconductor material of CdTe-technology itself contains the toxic cadmium (Cd).). Moreover, the paste used for screen printing front and back contacts contains traces of Pb and sometimes Cd as well. Furthermore, making monocrystalline panels tends to result in a lot of waste, as they are made from slices of silicon ingots leaving offcuts.

However, this waste can be used to make polycrystalline or multi-crystalline photovoltaic systems. In addition, the thin film silicon decreases the volume of the material by spraying a thin layer of silicon onto a surface, this has a potential impact and reduces waste. The recycling of photovoltaic equipment does need to be developed at the end of its life. The PV systems are being phased into waste electrical and electronic equipment. Finally, the manufacturer is responsible for the proper disposal and recycling the PV cells. They contain glass, and other valuable metals that can be extracted and used in either new solar panels, or exported to help build other devices. The recycling process is still fairly new to the industry, but once things get ironed out there will be a much better idea as to what to do with the used up panels. Perhaps a great new business idea before it becomes a dire need.

3.3.5 AC Battery Charger

One of the decided specifications of the PUVC is that it will be rechargeable by a wall outlet in addition to the solar panel. This provides the convenience of charging when at home or otherwise indoors and enables the PUVC battery to be recharged in non-ideal solar conditions such as at night or on an overcast day. It is important that the battery is properly charged to prolong the battery life and to keep the battery operation as safe as possible. In the early planning stages of the PUVC, charging the battery via a self designed PCB was considered. The BQ24450 by Texas Instruments was identified as a viable charge controller to be implemented into an AC charge controller. This charge controller has a voltage input range of 5 to 40 V which would mean that an AC/DC step down transformer would have to be connected between the wire from the wall outlet and the input of the circuit. This charge controller charges through constant current and constant voltage and includes an auto-cutoff feature but minimal protections. In the end it was decided that the AC charge controller would be purchased instead of being designed due to the complexity that arises by having a transformer involved as well as the safety risks associated with such a high voltage. The bq24550 would also need modification to provide short circuit and other protections which increases the difficulty in having it designed and printed on a circuit board. Instead we identified a suitable AC charge controller on the market which is a finished product that works out of the box.

The Beikalone 12V Sealed Lead Acid (SLA) Battery Charger was chosen for the AC charger of the PUVC. This charge controller costs $10 and is an automatic charger that charges at 14.8 V, 1300 mA. This charge rate is slightly higher than 0.1 C of the 12 Ah battery which will be housed in the PUVC but is still under 25% of the capacity of the battery which makes for a healthy charge rate. This charger simply plugs into a standard wall outlet and has two alligator clips that attach to the terminals of the battery. One important feature of this automatic charger is that it has short circuit protection which is important in charging SLA batteries to mitigate safety hazards. The overdischarge and short circuit protections, low price and the suitable charge rate were all deciding factors in choosing this product for the charging of the PUVCs battery. It saves us the hassle in designing our own charger at a low cost.

3.3.6 Power Inverter

While most of the components in the PUVC will be powered by either 12 V DC or 5 V DC there are two essential components to be powered by 110 V aC power. These components are the UV lamp which has a high power output to ensure that the water is sterilized additional to the LED strips and the water circulator pump which will continuously move the water so that the UV light reaches the full volume of water as quickly as possible. While Webench provides a tool for designing DC/AC converters, it was decided that a 12 V to 110 V DC/AC converter would be purchased rather than designed. The inverter identified for this purpose is the Generac 200 Watt Power Inverter. According to the spec sheet of this inverter it takes an input of 12.8 V and outputs an AC voltage of 115 V at 60 Hz. This inverter ships from the US and is on sale at a price of $10 at the time of writing. It has only one power outlet so two of them would be needed for the PUVC - one for the lamp and one for the circulation pump. This inverter is well documented with user manual and specification sheets available online. It features low battery shutdown and overload protection and comes with alligator clips and wires for securely connecting to the 12 V SLA battery to be used in the PUVC. Figure 13 below shows a Generac power inverter.

3.3.7 Water pump

The water pumps will be used to move water from tank to tank in the PUVC. A few parameters were outlined before choosing the water pump to ensure that we keep within the design specifications of the project. We needed a water pump that was designed to connect to a battery and not straight into a wall outlet or can be easily converted to do so. The water pump is to be DC powered and connected to the battery and main housing to maintain the portability specification of the PUVC. In terms of flow rate, we determined that we do not need a very large flow rate since a relatively small volume of water is to be moved through the PUVC at a time as it is a portable device. At minimum it was desired that the PUVC has the ability to fill a 24 oz water bottle from empty with the sanitized water in 10 minutes once it is properly vetted to be potable. Once the PUVC is able to confirm it is capable of killing the coliform present it will then allow for more rapid processing. We aim to process the water at a rate of 24 oz per minute. This corresponds to a flow rate of 1440 oz/hour or ~ 43 liters/hour. It was also desired that the water pump be waterproof so that we have the option of placing the water pump into the tank during implementation of the design. Due to the mounting costs of the essential cleaning and analyzing materials it was necessary for the pump we are hoping to acquire to be affordable on account of our limited budget. Lastly on the parameters of the water pump, the lift of the pump was a factor in the selection of the water pump. The lift of a water pump is the vertical distance from the water source that the pump can draw from. We set a minimum lift of 12 inches so that the water pump would be able to pull water from the base of a 10 gallon water tank which has a height of 12 inches. Fortunately, most water pumps far exceed this minimum lift parameter

3.3.7.1 Machifit DC 5V 12V 6W Water Pump

This water pump uses an ultra-quiet (<35 dB) mini brushless motor. It is DC powered and comes in either 5 V or 12 V ratings which are ideal for a battery powered project such as this one. It is a relatively low power electronic device at 2.4 W with a rated current of 480 mA for the 5 V model and 6 W with a rated current of 500 mA for the 12 V model. The power requirements aren't too high which provides the advantage of a longer run time on a full battery charge. With a flow rate of 250 L/H for the 5 V model and 300 L/H for the 12 V model this meets the requirement of being able to fill a 24 oz water bottle in 20 seconds by more than double the required flow rate. It uses a USB female plug which is less than ideal for connecting to a battery as it would require extra design, parts and soldering to facilitate a secure connection to the battery. This model of water pump also meets the waterproof requirement as they are fully submersible as well as the requirement of a 12 inch lift of 6.5 feet for the 5V pump and 10 feet for the 12 V pump. The fact that it is an ultra quiet pump is a nice benefit but isn't a specification of the design of the PUVC. Both the 5 V and the 12 V are very affordable $6.45 plus shipping. The 12 V model's advantages over the 5 V model are its greater flow rate and max lift, however, the drawback in choosing the 12 V model over the 5 V model is that it has a greater power requirement and will drain the battery of the project more quickly. This water pump is sold on Banggood and ships from China which could lead to long shipping times and other complications in acquiring the product.

3.3.7.2 Decdeal DC12V 5W Ultra-quiet Mini Brushless Water Pump

This water pump also uses an ultra-quiet mini brushless motor and has similar specs to the motor described in 3.3.7.1. It is a 12V, 5W water pump with a maximum current of 416 mA which is a fairly low power requirement for a motor. The Decdeal 12V motor has 40 inch long black and red wires for powering which makes it easy to solder to a PCB and also provides enough wire length so that the PCB will not come into close contact with the water and the water pump. It has a flow rate of 280L/H which corresponds to a 9 second fill time for a 24 oz water bottle - more than double the desired flow rate. The lift of this water pump is roughly 10 feet and it has a waterproof rating of IP68 which means it is fully submersible. The water pump also has 4 rubber suckers on the bottom which gives us the option of attaching it to the inside of the water tank if desired. This water pump is moderately expensive at $9.47 a piece and is sold by Walmart in the U.S.

3.3.7.3 Allnice Mini Submersible Water Pump

This water pump is a 12 V electric brushless water pump with a power rating of 4.8 W. The maximum current of this water pump was not given by the seller and no datasheet on this water pump could be found. It has a flow rate of 240 L/H and a max lift of 9.8 feet both of which meet the requirements for this project. It has an IP68 waterproof rating and is comparatively noisy at 40 dB. It has a 1.4 foot power cord in the form of a red and black wire. This water pump is moderately expensive at $11.99 but is sold in the U.S on amazon and has a shipping time of 6 days.

3.3.7.4 Comparison of water pumps

The water pumps' specifications are summarized in table 10. We ultimately decided to go with the Decdeal 12 V 5 W water pump as it meets all the parameters outlined in this section and is affordable at $9.47. Numerous water pumps were considered before settling on this option. The major contenders for water pumps that were researched and considered are outlined later in the section.

Table 10: Spec. comparison between water pumps

Manufacturer	Machifit	Decdeal	Allnice
Voltage Rating	12V/ 5V	12 V	12 V
Max. Current Rating	500 mA	416 mA	-
Flow rate	250 L/H	280 L/H	240 L/H
Max Lift	6.5 ft/ 10 ft	10 ft	9.8 ft
Cable length	-	40 in.	16.8 in.
Vendor location	China	U.S	U.S
Cost	$6.45	$9.47	$11.99

3.3.8 Charge controller selection

Based on the charge controller research presented in section 3.2.12 the maximum power point tracking controller would appear to be the optimal controller for solar charging. However at a solar panel Vmp voltage of 17-19 V for charging a 12 V battery a PWM and MPPT charge controllers will have a similar performance. Additionally, MPPT charge controllers are generally very expensive as many of them cost hundreds of dollars while PWM are quite cheap. For this reason the PWM is most suitable for the needs of the project. Once it was decided that PWM controllers would be used, we narrowed our search criteria for solar charge controllers and started looking at the PWM controllers available on the market to determine the best one for the PUVC. We ultimately ended up choosing the Binen 20 A solar controller as the charge controller for the PUVC. It was chosen on account of its low price of $15 especially as the budget for this project was limited.

3.3.8.1 Morningstar SG-4 Sunguard solar controller

The Morningstar Sungard controller is a PWM charge controller design for small systems. This charge controller is well documented on the seller's website and its datasheets are provided. It has a nominal voltage of 12 V to match the 12 V battery to be used and has a charge rating of 4.5 Amps which is more than enough for our 12 Ah battery. The self consumption rate is quite low at 6 mA and the voltage accuracy is 60 mV. It is designed specifically for a lead-acid battery which will be used in the PUVCThis charge controller is small at dimensions of 2.5 x 2.0 x 1.5 inches which is a plus for portability. It costs about $30 and the fact that its documentation is provided makes it a solid contender for the PUVC.

3.3.8.2 Binen 20 A solar charge controller

The Binen 20 A solar charge controller is a cheap controller sold at a price of $14.99. It comes with an LCD display that indicates the charge status and charging voltage. It comes with battery protections such as short-circuit protection, open-circuit protection,reverse protection and overload protection. This charge controller is a 3-stage PWM charger. This controller is intended for indoor use as it is not waterproof and has a working temperature of -35°C to +60°C. This fact is a drawback for use in the PUVC unless a waterproof enclosure is designed for it and temperature sensors are set up to keep it within working temperatures.

3.3.9 Reagent Kit Selection for Water Quality Analysis

To determine the quality of the water, coliform reagent tests will be performed on the sample to determine whether coliforms are present. Coliforms are a mostly benign group of bacteria that exist in the environment as well as the feces of warm blooded animals. While coliforms aren't likely to cause illness in humans, their presence in water indicates that there is the potential for disease causing bacteria to also be present, such as a specific type of coliform bacteria, E-Coli. Testing for all types of pathogens in water is expensive and complex, but testing for coliforms specifically is cheap and easy. Most pathogens in water come from the feces of warm blooded animals so while coliform testing can't provide a complete guarantee that water is safe to drink, it's a strong indicator that it is.

The way these kits general work is by adding a reagent to a water sample. The sample is then shaken up to evenly spend the reagent powder in the sample. This reagent provides nutrients to potential bacteria in the water which accelerates growth. The sample is left to sit for 24-48 hours depending on the temperature it's stored at. The warmer the temperature the shorter it takes to determine the presences of coliforms. It takes about 24 hours for a sample kept at 90-100 degrees Fahrenheit and about 48 hours for samples kept at 70-80 degrees Fahrenheit. During this time period the sample will undergo a color change to indicate the presence of coliforms. Some kits will have a color change even if the test does not detect the presence of coliforms but this color change will be distinctly different from that of a positive test. The optics in the analysis tank will view this color change to determine a positive or negative result for coliforms. There are a few commercially available test kits for home use that were considered for use in the PUVC water analysis tank.

3.3.9.1 Clean Water Store's Coliform Bacteria EZ Test

This kit retails for $16.90 and is available for immediate shipping. The EZ test comes with a warming pad that will keep the sample at 90 degrees accelerating the time it takes to show a positive result. The reagent used in this kit is safe and non-toxic. When the reagent is added to the water sample there will be an immediate slight color change to a clear-yellow color as result of mixing in the reagent. If no coliforms are detected the sample will remain this color indefinitely. If coliforms are present the sample will turn to a blue-green color over the courses of 24-48 hours. This kit also has the option to include a UV light for an additional $8 dollars. The purpose of this light is to illuminate a positive sample for coliforms. If the sample fluoresces with a blue color when illuminated by the UV light, then the sample is also positive for E-Coli. E-Coli is a dangerous pathogen and any sample positive for E-Coli should be handled with extreme care. Harm prevention standards for handling positive results will be discussed later on in the document in section 4.1.1 on Water Treatment Standards.

3.3.9.2 AquaVial Water Test Kit

This kit retails for $23.49 and is available for immediate shipping from Amazon. This kit uses proprietary dyes used to detect enzymes specific to coliform bacteria. The enzymes when present in large enough quantities will turn the color of the dye from bright yellow to bright purple. This test kit is sensitive enough to detect as little as 1 bacteria per mL of water. The color reaction for this kit takes 48 hours at room temperature and just 24 hour is the sample is warmed to 95-105 degrees Fahrenheit. This kit doesn't come with a warming pad or any other incubation equipment. This test however can't differentiate harmless coliforms from E-coli unlike the Clean Water Store's EZ test.

3.3.9.3 Readycult Coliform Test Snap Pack

This kit retails for $269.00 and has 20 snap packs containing the chemical reagent. This test has EPA approved testing protocol and EPA approved rapid presence test for the presence of both coliforms and E-Coli. This test operates very similarly to the Clean Water Store's EZ test. It had no distinct color change from a negative result, just a slight color change from the reagent being mixed in. A positive result for coliform bacteria will turn a blue-green color after 24 hours of incubation at 95-98 degrees Fahrenheit, and if illuminated under 365nm UV light will fluoresce blue to indicate the presence of E-Coli. The main difference between the two is this one comes with many samples for multiple trials, and the reagent is delivered in a snap pack to add to a water sample opposed to a jar to add a water sample to. It's a small detail but it's a nice feature to avoid exposing ourselves to risk associated with handling these reagents by using a snap pack to add the regent to the water rather than transferring them from a provided jar into the PUVC water analysis module.

3.3.9.4 Reageant Selection Consideration

The Clean Water Store's Coliform Bacteria EZ test was chosen for use in the PUVC water analysis modules because of its cost, flexibility and well defined color change. As initially proposed detection of E-Coli specifically is out of the scope of what the PUVC analysis module is required to do, but the fact that this test allows for E-coli detection when the sample is illuminated by 365nm UV light leaves room for improvements of the PUVC analysis module if desired in the future. Because this kit only exhibits a noticeable color change when positive for coliforms there is more room for error with the optics designed to view the color of the sample. Differentiating between two colors is harder than differentiating between a mostly clear sample and a colored sample. The optical setup should be able to differentiate between colors but there is no need to take on a harder analysis when an easier method is available at a lower cost.

3.3.10 Microcontroller Selection for Optical Analysis Tank

The microcontroller used for the PUVC will be responsible for powering the sensor, light source and processing the information obtained by the sensor to determine the color of the water sample which is how the quality of the water will be assessed. There are a few commercially available microcontrollers that are designed for DIY and amateur projects. Three options were considered for use in the PUVC optical analysis tank, the Raspberry Pi 4 Model B, the Adafruit Trinket MO and the Arduino UNO.

3.3.10.1 Raspberry Pi

The Raspberry Pi is a credit card sized board that starts at $35 and goes up from there with three options for on board RAM, 2GB, 4GB and 8GB, with 8GB option costing $75. The Raspberry Pi has a Broadcom BCM2711, 1.5GHz Quad core Cortex-A72 (ARM v8) 64-bit SoC chip on board. It has ports ethernet, USB, micro HDMI, USB-C and bluetooth connectivity. There is a micro-SD card slot for loading the OS and data storage. The board runs on a 5V DC with a minimum of 3A that can connect via USB-C or GPOI header. The board can run on a good quality 2.5A power supply as long as downstream peripherals consume less than 500mA. It can operate in an ambient temperature of 0-50 degrees C. The Raspberry Pi was chosen to operate the electronics in the PUVCs main cleaning tank and UI and further discussion of its capabilities are discussed in section 6.7 on MCUs. The difference of the Raspberry Pi compared to the other two options is the ability to run a full OS on the board allowing for far more computationally expensive processes to be run.

3.3.10.2 Adafruit Trinket MO

The Adafruit Trinket MO is a very small, quarter size board that starts at $8.95. It has a ATSAMD21E18 32-bit Cortex M0+ chip on board. It runs a 48 MHz 32 bit processor and 32Kb of RAM. It can flash 256Kb onto the chip. It can run software writing in popular languages like python and can be used with Arduino IDE and Circuit Python which comes loaded on the chip. It has a built in RGB LED which is a useful addition for the application in the PUVC analysis tank. It has 5 GPIO pins with digital input/output, 3 I/O pins can be used for 12bit analog inputs, and 1 I/O pin that can be used for 10bit analog outputs. It also has two high speed PWM outputs that can power external LEDs and servos. It can be powered by either USB or external battery. This board is extremely compact and convenient but does lack the processing power of the other two options but at a much lower cost.

3.3.10.3 Arduino UNO

The Arduino is similar in size to the Raspberry Pi and costs $23.00. There are a lot of similarities between this board and Raspberry Pi. The Arduino has its own development environment, Arduino IDE, that makes programming the microcontroller easy and beginner friendly. There are 14 digital I/O pins, 6 analog input pins and a 14 MHz resonator. It has USB connectivity, and can be powered by either USB, AC to DC adapter or a battery. The Arduino is designed to be very user friendly and the native environment for development makes it a very attractive choice for the project.

3.3.10.4 Microcontroller Selection

The Arduino microcontroller was selected because it was designed specifically for creating devices that interact with their environment using sensors and actuators. The Arduino's integrated development environment (IDE) makes programming it very simple. It is also very low cost and compact which is good for the economic budget and size budget of the device.

3.3.11 Sensor Selection

There are two types of devices typically used as light detecting sensors, photodiodes and photoresistors. Within the category of photodiodes there are a myriad of types of photodiodes and materials used to make the semiconductor chips to make them sensitive to different spectrums of light. Photodiodes have some key advantages that make them an attractive choice for light sensing over photoresistors. Photodiodes have a very quick response time on the order 5-25nS, which varies with different types of photodiodes and bias levels. Photodiodes are also typically far more precise then photoresistors and are used in sensitive equipment such as spectrometers. This is because photoresistors even of the same make, model and even batch tend to act slightly different from each other leading to inconsistencies. Photodiodes produce unidirectional current and operate in two modes, on and off. When photodiodes are on the voltage across the diode is increased and current flows. Some types of photodiodes considered for the sensor for this project include a PN type, PIN type, Schottky type and avalanche type.

3.3.11.1 PN Type

The PN type was the first type of diode to be developed and as such it is not as advanced for specific application and therefore isn't as widely used. The photodetection of a PN diode occurs in the depletion region of the diode which is very small in this type. Because this region is very small the sensitivity of this type of diode is poor. The lifetime of these devices is long and they offer low noise. It has very low dark current levels but also very low offset in current when on, which in some applications may not be high enough to drive the circuit.

3.3.11.2 PIN Type

The PIN type offers additional sensitivity and performance over the PN type. In the PIN type there is a large intrinsic layer between the PN junction. This large intrinsic layer results in a much larger depletion region compared to the PN type and therefore a much greater sensitivity. The larger intrinsic layer also reduces capacitance and therefore response time by as much as 1/10th that of PN types. PIN diodes when designed properly for the spectrum applicappable are very insensitive to changes in angle of incidence, in other words they are very good at collecting light that doesn't impinge perpendicularly. Reverse bias mode is required to operate these types of diodes which introduces a noise current, lowering the signal to noise ratio of the device. The reverse bias mode does however offer better performance for high dynamic range and high bandwidth applications. Both the PN and PIN type produce a linear response which is a key performance characteristic for many applications.

3.3.11.3 Avalanche Type

Avalanche photodiodes are used in a number of niche applications for a specific performance that other diodes cannot obtain. The main characteristic of avalanche photodiodes is high gain as a result of the avalanche process as the name implies. These diodes are operated under high reverse bias and designed to be operated in reverse breakdown voltage, a mode that would damage other types of diodes. This enables the avalanche multiplication of electron hole pairs created by light interaction with the device. As photons enter the depletion region and generate electron hole pairs the high electric field resulting from the bias condition pulls the carriers apart at high velocity. At this velocity carriers will collide with the lattice structure creating more electron hole pairs. This becomes an exponentially increasing process increasing the gain of the device many times over. The gain on these devices increases as reverse bias voltage increases and can rise to be on the order of 1000. This type of diode has very good sensitivity and is often used for detection at low light levels. To achieve this level of gain however very high voltages are required, sometimes as much as 1500V. Due to the avalanche process these diodes have a significantly higher noise level and a non-linear response. They also generally have a shorter lifetime then the PN and PIN types and therefore less reliability. The disadvantages and niche applications of this diode type make it far less common than the previous two choices.

3.3.11.4 Schottky Type

Schottky photodiodes are a unique type of diode that utilizes a metal-semiconductor junction instead of a PN junction. Photons pass through a thin transmissive layer of metal, often gold and are absorbed into the N layer of the semiconductor. The structure and operation of Schottky photodiodes is similar to that of PIN photodiodes, the main difference is the replacement of P type layer with the metal layer. Because Schottky photodiodes lack the P type layer there is no remnant diffusion tail arising from the generation of electron hole pairs, this results in an improved response time. Commercially available Schottky diodes can provide bandwidths of 25-60 GHz There are also some practical advantages of the Schottky type due to the metal junction requiring only 1 connection to be made to the external circuit, this advantage isn't paramount however for the application for this design. The primary disadvantage of Schottky photodiodes is poor efficiency resulting from reflections at the metal interface, this is especially problematic for longer wavelengths. Often anti-reflective coatings are to increase efficiency but the coatings are only effective for narrow wavelength ranges. These diodes are often used in applications where high speeds are required and some efficiency can be tolerated.

3.3.11.5 Photoresistors

Photoresistors are much simpler then photodiodes in operation and come in less variety. There is no cost advantage to either option, as both are very cheap ranging from $1-$10 per sensor. There is however a key feature of photoresistors that ultimately make them a better choice then photodiodes for this design. This feature is the analog nature of photoresistors, while photodiodes operate in a binary on and off state, photoresistors change in resistance across a spectrum of light and can take on many values of resistance. This allows for an analog voltage reading by the microcontroller which can be used to determine the color of light shone on the device with software processing. All photoresistors operate under the same principle, as light is shone on the device, its resistance is reduced. The only difference between types of photoresistors is the doping materials chosen which give sensitivity to different regions of the optical spectrum. These materials can be sensitive to UV, visible light, near and far IR.

Photoresistors in use today are made up of a variety of materials depending on the application of the resistor. The most common materials used are Cadmium Sulfide, Cadmium Selenide, Lead Sulfide and Lead Selenide. For this design Cadmium Sulfide is chosen to form the active layer of the photocell. Cadmium Sulfide is chosen because the spectral response of this material has excellent correlation with the spectral response of the human eye [19] as shown below in figure 14. The Lead materials are ignored for this application because the Lead materials have a lower response in general and have little to no response over the visible spectrum. Lead materials have their peak spectral response in the IR range which does have many applications but for the purpose of detecting a color change in the water sample, it is better to have a detector that sees colors the same way humans do.

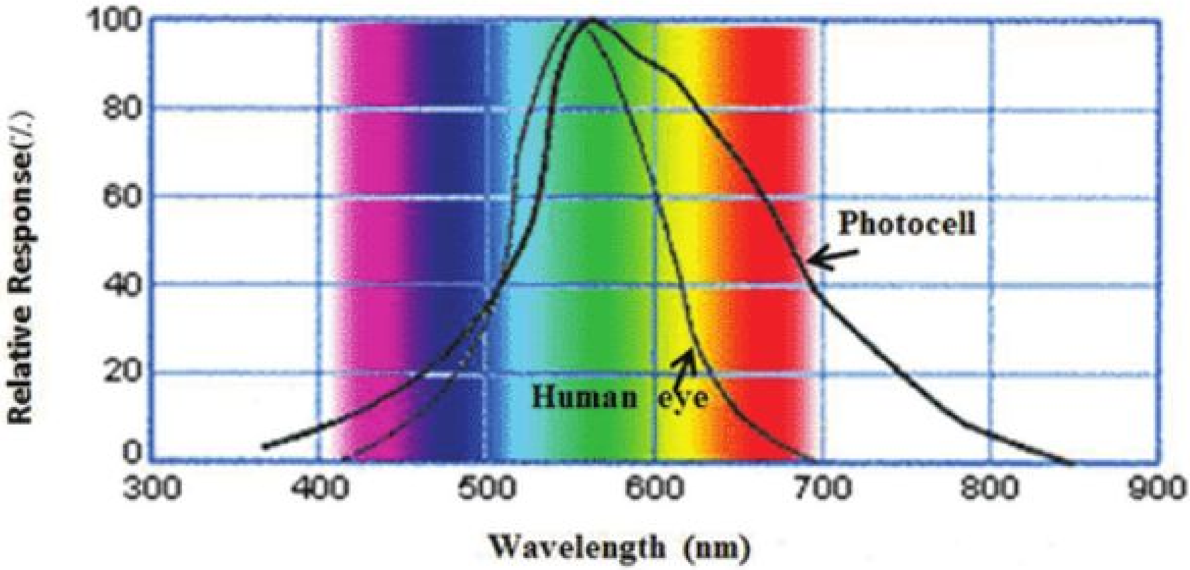

Figure 13: A comparison of the spectral response of a CdS photocell and the human eye

(Reprinted with permission of Seyed Salman Zakariaee)

The CdS photocell is an extrinsic semiconductor. An extrinsic material is preferred over intrinsic because intrinsic materials are generally far less efficient because the only available electrons are in the valence band and require more energy to be excited to the conduction band compared to extrinsic materials. The dopants in the extrinsic semiconductor are chosen such that the ground state energy levels of the materials are much closer to the conduction band of the base material and thus require less energy to be excited into the conduction band. A small amount of dopants can make a large difference in terms of efficiency and is why extrinsic semiconductors are used almost universally in photosensors.

A Photoresistor is able to detect subtle differences in light but do exhibit latency when responding to changes in light intensity. When exposed to light there is a delay in the subsequent decrease in resistivity of the device, often around 10ms. This latency is even longer when the photoresistor changes from a lit environment to a dark environment, as long as 1 second. Photodiodes also experience some latency associated with capacitances of the PN junction but these latencies are on the order of nano and microseconds. This property makes photoresistors poor detectors for rapidly changing lights. Photoresistors are often very imprecise with varying performance between devices made of the same materials. These two properties make photoresistors a poor choice of detectors for precise measurements or measurements involving rapidly changing lighting environments. Neither of these factors are a concern for this design as the lighting environment won't change rapidly giving the device ample time to respond. The method also does not require very precise recognition of color, it must only be able to differentiate between two different colors rather than two hues of the same color. This makes photoresistors an attractive option over photodiodes for this design because of their simplicity.

3.3.11.5.1 Vendor Selection

Vendors for photocells were compared based on three key factors, resistivity range which is important for considerations later in circuit design, lead time which is especially important due to the development of this design during the covid-19 pandemic and cost. The Adafruit vendor was chosen because its resistivity range is applicable to circuit design for this device and it ships from within the United States for a fast lead time. Table 11 below shows comparison of CdS photocell vendors.

Table 11: Comparison of CdS Photocell Vendors

Manufacturer	**Adafruit**	**BC Robotics**	**GikFun**
Resistivity Range	10kΩ-1kΩ	500kΩ-500Ω	10kΩ-800Ω
Lead Time	3 Days	2-10 Business Days	5 Days
Cost with Shipping	$9.94	$8.31	$5.78

3.3.12 Light Source Selection for Basic Spectrum Analysis

In order to perform a spectrum analysis on the water sample a light source will be used to illuminate the water sample that is ultimately viewed by the CdS photocell sensor. There are two primary options for light sources, LEDs and Flashlamps.

3.3.12.1 Flashlamps

Flashlamps are an electrical arc lamp designed to produce high intensity, incoherent, broad spectrum light. Typically flashlamps are a sealed glass tube containing noble gases, usually xenon, with two electrodes at each end supplying the current to the gas. A charged capacitor is usually used to supply energy to flash, allowing for quick delivery of high energy current to electrodes when the lamp is turned on. The gas inside the flashlamp can be changed or the glass envelope containing the gas can be doped with different materials to alter the spectrum output of the lamp. Flash lamps tend to be larger and less compact than LEDs and require more power to use. They do however output more power than LEDs at the cost of efficiency. For the purposes of the PUVC a spectrum over the visible range is desired. A few commercially available flashlamp products were considered for the PUVC optical analysis tank.

3.3.12.1.1 HPR-8059 Round 8400ws Flash Tube Quartz Lamp

This Flashlamp is fairly compact with dimensions 70x66mm and has a very broad spectrum of light ranging from UV to visible light. It can be operated at a variety of voltage levels ranging from 250-700V. It can output a maximum flash energy of 4800J. The cost of this lamp is $219.00. This lamp would provide a broad high intensity spectrum to illuminate the water sample, but the power requirements are prohibitive for the portability of the device. This cost is also quite high for the final price point of the PUVC.

3.3.12.1.2 High Output Heraeus Xenon Flash Lamp

This lamp comes in three versions 7W, 16W and a 16W version with an extended envelope for a longer lifetime and improved performance. It also has two different window materials with different transmission spectrums. The UV glass window outputs a spectrum ranging from 190-3500nm and the Borosilicate glass has an output spectrum ranging from 300-4500nm. This manufacturer lists a series of photonic applications the lamp was designed for including spectrophotometry, spectroscopy and color analysis. The lamp is rated for a lifetime of more than 109 flashes. A quote has been requested from the manufacturer for the device, but based on similar products the expected price point is around $300. The dimensions for this lamp are not included on the data sheet but it appears to fit on a small board. This seems like a good option for the application needed, but the price point will likely make it nonviable.

3.3.12.2 LED

Compared to flashlamps LEDs are much more compact, cheap, draw less power, and are more efficient. LEDs could be powered directly by the microcontroller and will still provide enough optical power to meet the needs of the PUVC analysis tank. For these reasons an LED will be used over a flashlamp.

The RGB LED is chosen because red, green and blue are primary colors. Primary colors are colors that cannot be mixed from a combination of other colors. The human eye has 3 types of cones that sense light. Each of these 3 types correspond to the primary colors, meaning these are the colors sensitive to the human eye. Combinations of primary colors can yield millions of different colors and hues. These secondary colors and hues are created by different proportions of primary colors. For example 1 unit of green combined with 1 unit of red, produces the color yellow, 1 unit of green combined with 2 units of red, produces the color orange. 1 unit of red, 1 unit of blue and 1 unit of green will produce white light. Figure 15 below shows how primary colors combine additively.

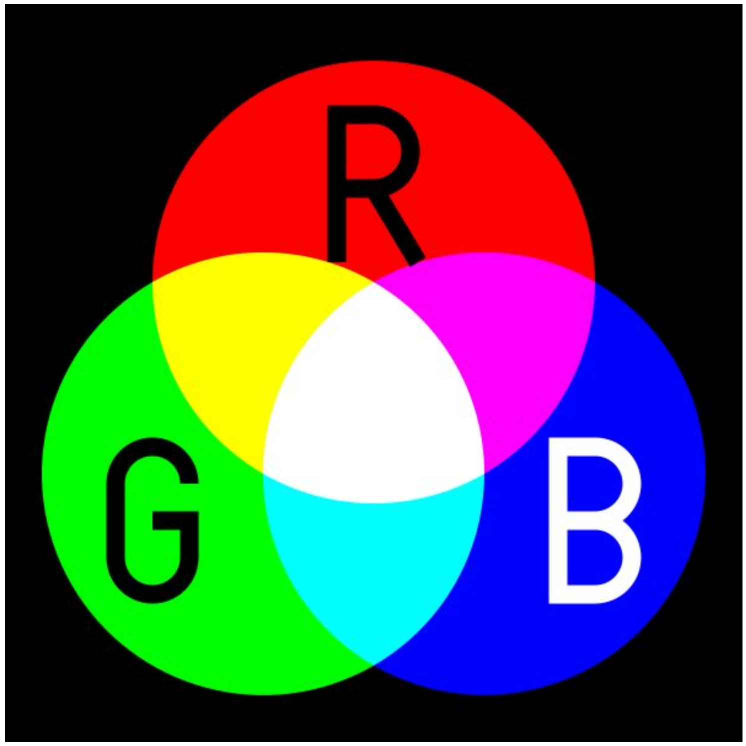

Figure 14: This figure shows how colors additively form white light

(Reprinted with permission of SharkD)

3.3.12.2.1 RGB LED Vendor Selection

Vendors for RGB LEDs were compared based on similar factors as the photocells, lead time, cost and compatibility with the voltage output on the microcontroller. The Kingsbright WP154A4SEJ3VBDZGC/CA RGB LED was chosen because its cost effective, ships from the United States and compatible with the microcontroller. Table 12 below shows the LED vendors comparisons.

Table 12: Comparison of LED Vendors

Manufacturer	*Kingbright*	*Sparkfun Electronics*	*Adafruit*
Compatible	Yes	Yes	Yes
Lead Time	2 weeks	2 weeks	12 weeks
Cost with Shipping	$11.88	$9.98	$18.98

3.4 Possible Designs and Related Diagrams

Before any final design may be decided upon first several design iterations must be made. To ensure that our product made an attempt to fit all its engineering and marketing requirements we would have to go through many trial and error runs of design. As will be discussed in the following section the team will go over our initial design, its flaws and then how we worked around these initial constraints to end up with a final design. These constraints mainly surrounded being able to properly disinfect the water without outside contamination, protecting the user from UV exposure, and making a design that is indeed portable. Due to these constraints the design was changed from the initial three stage design to a more compact two stage unit. The two stage unit is also far smaller than the three stage unit as it does not contain tanks for water storage. The team decided to focus primarily on sanitation and analysis and remove the ability for the device to store water. More details on the design considerations can be found in the following sections 3.4.1 for the initial design and 3.4.2 for the final design.

3.4.1 Initial Three StageDesign

Shown in this section are the first iterations of the design that we went through before deciding on the final portable design we are presenting. Shown in figure 16 below is our first full design of the portable system designed in three separate phases. These phases were broken up by their distinct functions. The first tank pre-processed the water so that the UV could appropriately penetrate the water and so that various debris is eliminated from the water. Once the water passed through the second pump it would then enter the second sanitation tank. Within this sanitation tank is an array of LEDs focused by optics into the water at an even distribution. Once the water was exposed to the UV and appropriately cleaned it would then move to the final reservoir responsible for testing of the water. At first we attempted to categorize the water components through a spectroscopic process. This proved to be unachievable though due to the constraints the pandemic placed on creating a system capable of spectroscopy without a sponsor. The cost would be far too great to implement without additional aid from an outside source. Due to this the analysis technique was changed to an RGB color identification system in combination with a coliform test to verify the cleanliness of the water. This analysis would be performed in the last tank to verify whether the water was clean or still contaminated. Once the analysis was performed the tank would allow water output. Figure 17 below shows the unit in a more compact assembly as it was first envisioned.

As the team began outlining the actual design it soon became apparent that several changes must be made for the PUVC to be usable. The first flaw that was realized was the portability of the unit. Due to the three stage design the size of the PUVC soon became too large to be in fact portable. To remedy this the fill tank was removed and so was the large analysis tank. These were replaced with a more effective input pump array and smaller analysis unit. As already mentioned the analysis was also changed so that a more effective test method could be used and a more robust system could also be used. The user interface and electronic systems as they were still being developed were not fundamentally changed and as the main components had still not been decided upon. There were several other design flaws within the PUVC that were modified along the way to the final planned design. These considerations and others will be discussed in section 3.4.2.

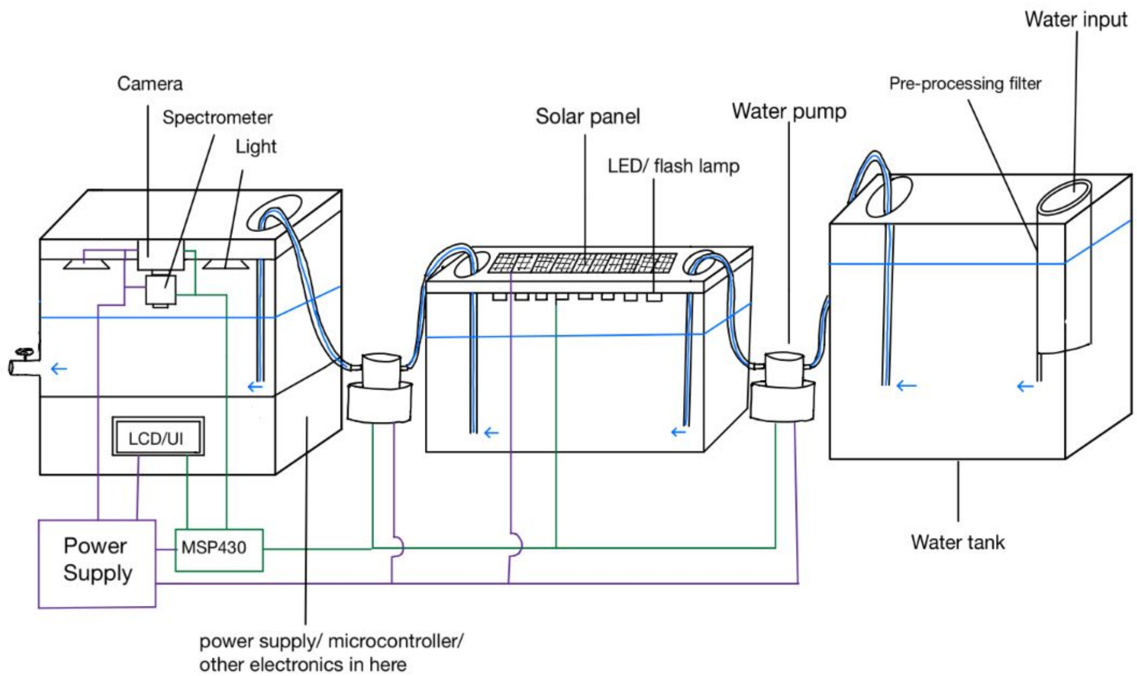

Figure 15: First full design iteration of portable uv sanitation

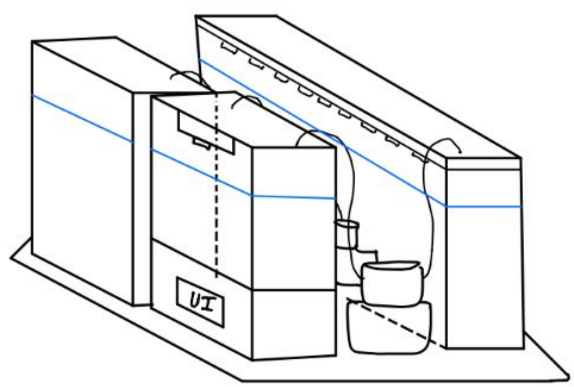

Figure 16: Compact view of initial design premise

The initial design gave us valuable insight into our idea and allowed us to think through a variety of scenarios the PUVC could be applied and what needed to be changed. Although we did not build a three stage design nor will we pursue it, it is important to understand how we got to the final design. Although at first the three stage design seemed like a viable option it was soon discovered that there were many inherent flaws in the design that would force a new design iteration. As discussed earlier in the section due to several inherent design flaws the design was changed to be more achievable with the current constraints, more portable, and more cost effective. The details of the final design are found in the section below.

3.4.2 Final Dual Stage Design

This final design came about after various other iterations of the PUVC. The team redesigned and reevaluated the PUVC as prototype development continued. As discussed in the previous section several flaws came to our attention that led to the creation of a more compact design capable of the same process. The final design involves a dual chamber setup instead of the three initially proposed in our design. The team decided due to the constraints around our project it would be best to focus on a system that was more portable but still offered the same capabilities. The PUVC in this design will work as a standalone unit capable of water sanitation in three phases. First the PUVC input hose will be connected to a water source cleared of visible debris, extract the water through a filter and pump, and pass the water through a LED ring array. Secondly the pre treated water will then flow into the sanitation chamber to be further irradiated. This stage will also serve as a holding tank while a small amount of water is drawn away for analysis. This leads to the third step in the process where a small portion of the cleaned water is then analyzed for its coliform content. Upon the completion of these three steps and a negative coliform test the PUVC will then allow the water to be dispensed. The major components behind this process and our planned designs for these components can be found in section 5,6 and 7.

The PUVC in this design will also employ two seperate LED arrays as well as an internal lamp for coliforms that require a higher UV dose. This measure was instituted because as we researched more extensively into the requirements of UVGI we realized that if we wanted the project to have real application in areas where there exists water that is highly contaminated, there would have to be a way to dramatically increase the output power. From our research we expect water from streams, rivers or any other moving source not connected to fecal contamination to be easily processable by the LED array. If this is not accomplished and the coliform test comes back positive several steps will occur. Firstly the contaminated water will be removed from the analysis tank and a small amount of bleach and water must be used to clean it. If this is not done no further tests will be able to verify the content of the water as the analysis tank will be contaminated. Upon the completion of the step the user will then run the high power lamp inside of the sanitation tank. This lamp is able to output a power of 18.4 Watts. This power is 46 times greater than the power produced from the LED array and nearly 70 times stronger than the LEDs used for additional irradiation within the tank. The lamp also produces as mentioned in section 3.3, an output power of 5.4 Watts of UVC. This amount of UVC is far greater than the amount needed for the volume of water and the coliform being targeted. This additional feature will provide a secondary option to kill more resilient coliform but will add additional time to the cleaning cycles. This will also be the secondary cleaning option as it will take a greater amount of energy to run the lamp than the LEDs alone. In totality the two stage design solves many of the issues that confronted the team earlier on with the three tank system and allows for a greater dose of UV to be delivered in a more affordable and portable package.

4.0 Standards and Design Constraints

This section will be used to establish more definitive standards for our design as well as explain the various constraints the team dealt with during the design process. The team due to the widely changing and never consistent COVID epidemic the team was unable to meet in person and only could contact each other online. In totality this section will cover the standards we have set for the PUVC so that we can confirm the device is functioning and a prototype can be achieved.

4.1 Standards

Standards are the established way of handling various tasks within an industry to ensure safety and interoperability. This project involves a multitude of devices and processes, many of which have well established standards. These standards were well researched in the initial phases of designing the UV water sanitization system and throughout the design of this project every decision that was made was done in keeping these standards. We outline some of the various standards in this section.

4.1.1 Water treatment standards

Some existing standards for water treatment of Coliforms given by the EPA:

- Total coliform samples must be collected by PWSs (Public Water Systems) at sites which are representative of water quality throughout the distribution system according to a written sample siting plan subject to state review and revision.
- The baseline monitoring frequency for seasonal systems is monthly
- For PWSs collecting more than one sample per month, collect total coliform samples at regular intervals throughout the month
- Each total coliform-positive (TC+) routine sample must be tested for the presence of E. coli
- If any TC+ sample is also E. coli-positive (EC+), then the EC+ sample result must be reported to the state by the end of the day that the PWS is notified.
- If any routine sample is TC+, repeat samples are required.
    - PWSs on quarterly or annual monitoring must take a minimum of three additional routine samples the month following a TC+ routine or repeat sample.
        - One repeat sample must be collected from the same tap as the original sample.
        - One repeat sample must be collected from within five service connections upstream.
        - One repeat sample must be collected from within five service connections downstream.
    - If one or more repeat sample is TC+:
        - The TC+ sample must be analyzed for the presence of E. coli.

        - If any repeat TC+ sample is also EC+, then the EC+ sample result must be reported to the state by the end of the day that the PWS is notified.

Based on the standard proposed by the EPA this design will adopt the following standards:

- Water quality analysis should be performed every time the tank is filled from a new water source
    - If the water source has been used previously, then the most recent test must be within 30 days.
    - When using water from the same source within 30 days of the previous sanitization analysis the operator may use the water without sanitization analysis in order to avoid a 24-48 hour lag time from fill time to use.
- If sample is TC positive after UV cleaning:
    - 1mL of bleach should be added to the sample and the sample should be agitated. The sample should then be carefully disposed of in a drain or toilet ensuring not to come into direct contact with the sample on the user's skin.
    - 5mL of bleach should be added to the tank and left to sit for 1 day. The entire tank should be emptied and the water should be disposed of in a drain.
    - The entire tank should be washed with bleach while wearing personal protective equipment such as latex gloves and rinsed thoroughly with clean water.
    - If a sample is TC positive twice in a row, the same procedure should be used to dispose of the sample and water in the tank. The user should immediately contact the manufacturer and cease use of the system.

4.1.2 Battery Standards

Battery standards were studied closely before design due to the inherent safety risks associated with using a lead-acid battery. IEEE Std 1361-2014, provides guidelines for selecting, charging, testing, and evaluating lead-acid batteries used in stand-alone photovoltaic (PV) systems (25). This standard recommends a few items that they consider mandatory for personal safety when testing batteries. These safety items include : goggles for eye protection, acid resistant gloves, eyewash stations (portable or stationary), electrolyte neutralizing solutions, protective clothing, and a class C fire extinguisher. The electrolyte neutralizing solution or powder must neutralize the standard electrolyte which is 20%-30% sulfuric acid solution. Baking soda is a viable option for this purpose. This standard warns of electric arc hazards from shorting the positive and negative terminals of the battery. The design impact of this standard is that short circuit protection will be included as one of the functions of the battery protection circuit. When lead-acid batteries are fully charged and charging is continued, hydrogen and oxygen gas are released as a product of the chemical reaction that occurs during the electrolysis of water. These gases are flammable and potentially explosive. Although, the National Electrical code mandates that lead-acid batteries have flame-arrester caps, to further mitigate the risks associated with this process the PUVC will be designed to have a charge controller that prevents overcharging of the battery. It will have an auto cutoff system that cuts off constant current and constant voltage once the voltage of 14.4 V is detected at the lead-acid battery.

This standard also offers a selection criteria of lead acid batteries for a PV system such as the PUVC. The standard suggests that battery life be maximized to minimize the overall cost of the system. Maximizing the battery life will save cost in the long run by prolonging operation before the inevitable battery replacement necessity arises. IEEE Std 1361-201 identifies flooded, deep cycle batteries as a good choice. Flooded deep cycle batteries are designed for repeated deep cycling which is often a feature of PV systems when recharging batteries. This recommendation will be taken into consideration in choosing a battery for the PUVC.

IEEE Std 1361-2014 also provides testing procedures and guidelines for lead-acid batteries. The testing proposed by this standard aims to simulate the daily charge and discharge cycles of a PV system - a result of fluctuating solar radiation throughout the day. The test procedure includes 25 shallow cycles and to simulate the high solar resource periods and 6 deficit charge cycles to low-voltage disconnect to simulate low solar resource periods. The testing standard calls for the following to be recorded: charge and discharge parameters, initial battery capacity, percent of overcharge in Ah for the first and last of the 25-sustaining charge cycles, total Ah discharged to LVD and test temperature among other parameters outlined in the full document. These identified parameters are what will be tested for the battery testing portion of the PUVC design.

4.2 Design Constraints

This section covers the design constraints we faced in the development of this project. Due to the fact that this project is being planned and executed in the midst of a global pandemic, COVID19, the environmental constraints are many. We also faced additional constraints in sanitizing the water considering that water contains a myriad of contaminants and its constituents vary wildly from environment to environment.

4.2.1 Economic Constraints

It has proven difficult to secure funding from local businesses and at the time of writing this document, no sponsorships or funding has been secured. On account of the fact that this project is being funded by the members of this group, there is a major budget constraint. Every component used in constructing this project has to be chosen with careful considerations of the budget. Extensive research has been put into comparing parts and the various trade offs at different price points to ensure that we are keeping within budget and that we are getting the best value for our money. For the objectives of this project, a microscope which has the capability to detect microscopic materials such as viruses and pyrogens can easily run into the hundreds and even thousands of dollars. This has forced us to get creative in coming up with an affordable method of detecting these microscopic materials.

Additionally the budget constraints present a challenge in part testing. After every component has been carefully chosen, utmost care is to be given for the components to avoid having to buy replacements. The limited budget leaves little room for trial and error and part malfunction due to design error. We simply might be unable to afford replacement parts. This fact necessitates that we prioritize selecting parts that are reliable and compatible with every other part in the project and that we minimize error when assembling the parts especially in avoiding simple errors such as burning components.

Another economic constraint for consideration is due to the unusual circumstance of undertaking this project during the COVID-19 pandemic. Shutdowns have the potential to limit our options in choosing parts resulting in us being unable to necessarily choose the part that gives us the best value for money. This is especially relevant when ordering parts from China. In some cases we may have to settle for a part, not because it is best suited for our project goals, but because it is the only one available. It may also cause prices of some items to rise as they become hard to obtain or there may be additional expenses associated with the shipping of the parts from overseas.

4.2.2 Time Constraints

The time frame of this project is set on account of the fact that Senior Design 1 and Senior Design 2 lasts 2 semesters. For this reason the major time constraint of this project is getting the project completed within those two semesters. This time frame roughly equates to 7 months where the project must be planned in Senior Design 1 and executed with demonstrable success by the end of Senior Design 2. It is also important that we order parts ahead of time because of long shipping times often associated with ordering electrical components especially during the ongoing pandemic which could lead to extra delays. We also want to ensure that we acquire and assemble the parts as soon as possible so that we have ample time for testing and troubleshooting. On top of this condensed time frame there are also major issues caused by the COVID pandemic. Any and all communication, meetings, testing and collaboration was severely delayed due to the current misunderstanding of how the contagious COVID forces the team to create new unique timelines and also formulate how anything would be achievable as a small self funded team given the current constraints. In conclusion the team was severely limited time wise, not only because of the established two semester deadline but also because various environmental constraints forced the delay of many key design stages.

4.2.3 Health and Safety Constraints

The health and safety of the users of this project are an important consideration in the design of this system. Since we are dealing with the sanitization of water the main health and safety concern is that of ensuring that the users do not get sick from water borne bacteria and other water related diseases. We clean the water in phases so that the potentially contaminated water never comes into contact with the water outlet. We also employ devices that detect the water contents after sanitization to ensure that the water has been purified and is free from any impurities that are harmful to human health. We would also like to ensure that the potentially contaminated water never comes into contact with the user during processing by using sealed containers and a closed system during processing. These steps will help reduce the risk of contamination from the water or potential pathogen exposure. The sanitation itself is also a major factor as the use of UVC diodes and lamps can be potentially harmful to human skin and eyes. These risks are a major factor as the UVC can produce a high power of ionizing wavelengths that if a medium length exposure occurs the users eyes could be at risk. Also over time if the device is cycled without proper protection the user could develop skin abnormalities such as skin lesions or even cancer in an extremely severe case(16, Rass). There are several easy solutions to this such as employing a lock on the lid that prevents use without the tank being closed.

Another health and safety concern is the risk associated with having water near electronic devices. If this risk is not taken into consideration in the design of this project it could pose a serious threat to the health of this user. In order to eliminate the dangers of having water come into contact with electrical components, this project was designed in such a way that the electronic components and water processing components are in separate compartments. The electronic components are stored and operated in an enclosure safe away from the water. The final health constraint that needed to be considered for the PUVC was to ensure that if the device confirmed a positive coliform test how could the PUVC be cleaned or provide additional sanitation. As of now the team's solution to this is to add a high power UV lamp to the sanitation chamber to provide an additional high dose of UV to kill coliform that requires a higher UV dose than the initial array can provide. Further testing will need to be done before this can be guaranteed and in the case that it is not possible to remove the coliform then a procedure will be utilized to clean the PUVC with a bleach solution.

4.2.4 Portability Constraints

In order for the PUVC to be implemented as envisioned it must be designed such that it is usable in potentially remote or undeveloped areas. To achieve this it must be small enough to be portable without requiring an unreasonable amount of effort for the user. The modular design was chosen to meet this constraint with a solution that allows for the PUVC to be transported in a compact fashion. The PUVC final design should be compact enough to be carried by two people on foot once it is broken down. A device such a backpack could be used to carry the device and would resemble an extra large hiking backpack ranging from 100-200L in size. The PUVC should weigh no more than 25 pounds while empty. The assembly and disassembly of the modules should be simple and require minimal tools.

In addition to size constraints, power must be considered for remote areas where electrical power isn’t available. The PUVC must be operable at a power level of 500 milliwatts or greater in combination with the LED and the lamp and will most likely far exceed this when employing the lamp. The solar array and battery for remote charging must be able to generate and store at least two cycles worth of power for the PUVC in under a 12 hour time frame. Ensuring the PUVC meets these constraints will ensure that that the device will be able to be usable when it is transported to a remote area or where a larger amount of water is needed to be processed than the battery bank can provide.

4.2.5 Testing Constraints

During the entire process of senior design one we have had one constant, no access to any school labs or facilities whatsoever. This has made it remarkably difficult to test an optics and photonics based project due to the inherent need for expensive equipment to be able to assess and diagnose almost any opto-electronic. To overcome this the team put extensive work into planning out our senior design 2 and also outlined all major tests we would like to perform so we know exactly what needs to work for the PUVC to work. As of the completion date of senior design 1 there are still no UCF students allowed on campus and the only method we have to get optical measurement devices is to put in a request and hope that one is available to be rented out. There also arose extra testing problems in that without a lab some of the sensitive electronics could be damaged. To work around this the team took it upon themselves to designate an area within their own homes where the electronics could be stored properly and assembled once the prototype began to take shape. The team does still believe even with these restraints that a functioning device can be created as once the devices are proved to work overall assembly should be fairly easy with the modular design we created. In conclusion the team had tremendous pressure to accomplish testing but were not given any facilities to do so. The team was able to adapt to circumstances never before experienced by undergraduate senior design students and we do feel that as facilities begin to open and more freedom is established the PUVC will come together quickly.

5.0 Optical Design

The optical design of the PUVC is composed of a variety of components. These components range from mechanical to electro-optical and provide our project with the ability to not only sanitize the water but also view the water to verify cleaning has occurred. This section will focus on the optical design that allows for effective cleaning in the PUVC and allows for the proper amount of power to be delivered into the water. The optical design of the system consists of three main components. These components are the initial UV high power array, low power scanning array and high power lamp for the sanitation tank , and the optical analysis device used to perform the coliform test. This section will focus on the optical devices as well as lenses that will allow for the PUVC to properly function.

5.1 UV High Power Array

As mentioned earlier in section 3 to allow for many of the coliforms present in the water to be eliminated a high enough power will have to be employed. The UV high power array will allow for the PUVC to potentially reduce its processing time if the water is not extremely contaminated with strong coliform then the initial UV array sanitation should be enough to eliminate any potential pathogens. The high power initial array will allow for the water to be sanitized within a rapid time period depending on the severity of contamination. The design consists of 10 UVC LEDs in series and embedded in a plexiglass and silica housing unit to protect them from the water. As shown in section 6 the design would consist of an input hole to allow for the water to pump into the array, a plexi-glass and quartz sanitation rectangle and an output hole for the water to exit. The exact dimensions and design plan are also found in section 6. The optical design of this component is simple as we did not want to accrue a lot of power loss due to a lens matrix. The main optical component to be considered is the UV fused silica window place in front of the UV arrays. This window will only be a few millimeters thick and will cause less than a 8 percent loss in power. This power loss will be further tested and explained in section 8.

In conclusion the high power array will allow for a rapid high dose of UVC irradiation to be delivered to the water before it enters the actual processing tank. Once an initial analysis is complete the high power array could potentially be used as the primary sanitation unit providing the PUVC with the ability to process water. More testing must be done first to verify the true power delivered to the water within the array. As of now it is estimated the array will deliver near 40 milliwatts to the water and for a duration of 2-5 seconds. This duration will allow for effective pre processing of the water. To ensure our design stays modular the array will also be able to be detached from the water pumps and sanitation unit.

5.2 UV Diode Tank Array

For the effective sanitation of the water, LEDs were chosen as they provide the greatest efficiency of power use. We also used LEDs as it created a more open tank design and allowed the LEDs to be embedded into the system protecting them from damage that could be caused by long term water exposure and to avoid the use of overcumersome lamps. The UV tank will attempt to employ five separate lenses to collimate and then redisperse the power from four UV LEDs placed within the tank. The lenses themselves have already been discussed in section 3.3 so further discussion on the material properties will not occur in this section. This section will focus on the three lenses put together to collimate the LED as well as the two lenses used to redistribute the light into a more hemispherical shape. We attempted to distribute the light into this shape because it better confined the irradiation of the UVC and would allow for a greater dose per square inch to be delivered.

5.2.1 Collimating Lense Matrix Design

In the team's opinion a collimated light source was the best choice to redistribute the UVC as we could better control the output profile. Without a collimating lens the light pattern may still diverge too quickly causing more dramatic power loss. To do this the optical array setup will be similar to that shown in figure 18 below. As can be seen the source will be aligned with an initial bi-convex lens, this lens will refocus the source into a bi-concave lens. The bi-concave lens will allow for the light to be re-directed and due to its negative curvature it will diverge the convergent concave lens beam. This re-divergent ray pattern will then enter a plano convex Given more testing this matrix may be able to be simplified to a simple aspheric lens if these lenses become more cost effective and available. Further testing needs to be done before a definitive collimation matrix can be decided upon for a production ready device. Testing of the lens array can be found in section 8 with its collimation effects.

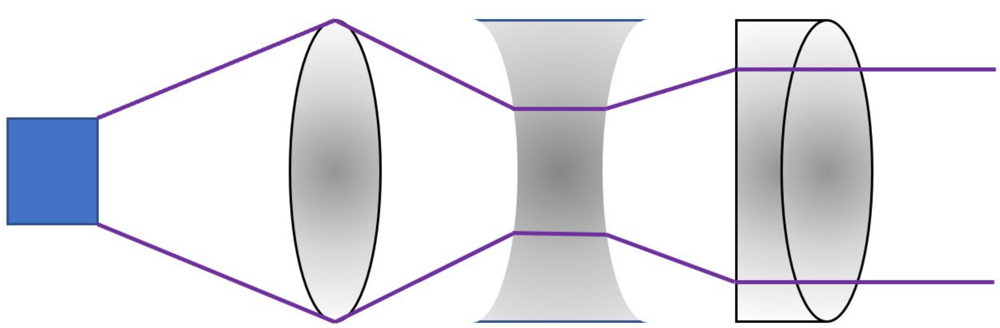

Figure 17: Collimating lens setup proposed for PUVC

Another option the team is weighing is whether the use of an aspheric lens would offer a better and more cost effective solution to collimating the LED. Due to funding and cost constraints the team did not buy an aspheric lens as the cost of that lens alone would total more than $700, far too great an amount for the team to spend.

5.3 UV output monitoring

To ensure that the UVC LEDs are in fact on there must be a method for monitoring the UV output. It is not necessary within our project to define a known output spectrum of the UV LED therefore no measures will be taken to obtain the spectral information. To do this would also add additional cost that is already over budget. As a simple solution the team has laid out the inclusion of a camera in the top of the PUVC. This camera will allow for the user to see inside the tank to ensure that the UV LEDs or lamp is indeed functioning. The high power UV LED array will not be constantly monitored as it will be partially visible to the user. The camera will be covered by a small glass shileidng to reflect the UVC rays that could damage the electronics. There will be a faint glow produced by the LEDs that will be visible to the eye and will be visible on the user interface.

5.4 Color Sensing

In order to determine the success or failure of the UV cleaning of the water sample a simple chemical reagent test will be used. The reagent will produce a different color change in the water for a positive and negative result for coliforms in the water. The difference in color provides an avenue for optical analysis via color sensing.

5.4.1 CdS Photocell

The first component necessary for the color sensor design is a CdS photocell. A photocell is just a variable resistor whose resistivity changes with the amount of light shone on it. The higher the light intensity shone on the device, the lower the resistance. With no light the photocell has its peak resistivity. When light is shining, the material absorbs incoming photons causing electrons in the material to move from the valence band to the conduction band. Electrons in the conduction band have enough energy to move freely and thus the resistivity of the device is reduced.

A voltage will be applied to the photocell which will be connected in series with a resistor. An analog voltage measurement will be taken between the photocell and resistor. This voltage reading will be used to determine the color of the water sample. The photocell used for the PUVC color analysis tank is shown below in figure 18:

Figure 18: Two CdS photocells

5.4.2 RGB LED

The next component necessary for the color sensor design is a Red Green Blue LED. The purpose of the LED is to illuminate the sample at different wavelengths. The LED used in the PUVC color analysis tank is shown below in figure 19.

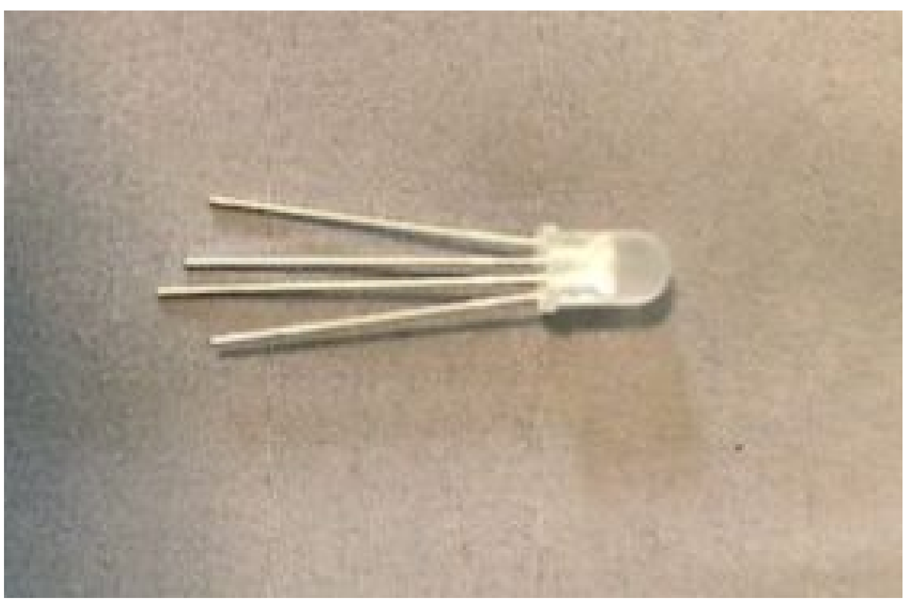

Figure 19: RGB LED used in the PUVC analysis tank

Different materials will interact with light in some combination of transmission, absorption and reflection. Absorption occurs when light is converted to thermal energy within an object.

Electrons in atoms vibrate with a natural frequency, when light of the same frequency impinges on one of these electrons, it's set into a vibrational motion. This vibrational motion causes the electron to interact with neighboring atoms and elections. This interaction converts vibrational energy to thermal energy. Once converted to thermal energy the light ceases to exist and never exits the object. The selective absorption of light of specific frequencies is a material property. Different materials have different vibrational frequencies and thus absorb different frequencies of light. This material property plays a large role in how humans perceive the color of an object.

Reflection and transmission occur when the frequency of light impinged upon a material's electrons do not match its natural vibration. When light of these frequencies strike an electron, it briefly begins to vibrate in a similar fashion to when light is absorbed, however this vibration is not in resonance with the natural vibration of the electrons in the material and the energy is quickly reemitted as a light wave. For transparent objects like water the vibrations of the electrons are passed on to neighboring atoms as they travel through the material and re-emit on the opposite side of the object. These frequencies are said to be transmitted. For opaque objects the vibrations occur on the surface of the object and are reemitted as a light wave. These frequencies are said to be reflected. Many liquids including water are highly transparent, meaning they transmit most of the light that it interacts with. This will become an important fact to consider for the design to be discussed further later.

So the color of an object is determined by which frequencies of light it absorbs and which frequencies it transmits and reflects, a result of the natural vibrations of the electrons within the material. Color does not come from the object itself, rather it comes from light shone upon an object that is then transmitted or reflected off the object and into the human eye.

5.4.3 Arduino Microcontroller

The final component needed for the optical analysis is an Arduino UNO microcontroller. The Arduino is required in order to interpret and process the response of the CdS photocell. The CdS photocell collects light but on its own can't do anything with the information. The Arduino is used to interpret the wavelength of light impinged on the photocell based on the response of the CdS photocell. The cell is particularly responsive to green-yellow light. When this light shines on the photocell the voltage across the cell is reduced compared to when red light is impinged upon the cell. This difference in voltage is interpreted by the Arduino to determine the frequency of light and can be processed further to determine the proportions of light at different frequencies. Figure 20 below shows the board used for the PUVC.

Figure 20: Arduino UNO board used for the PUVC analysis tank

5.4.4 Optical Sensing Method

The optical method to sense the color of the water sample involves operating the LED with equal proportions of the primary colors to produce white light. The light from the LED will illuminate the water sample and some frequencies will be absorbed and some will be reflected and transmitted based on the color of the water sample. The CdS photocell will view that water sample and collect the reflected light. The light collected by the photocell can then be analyzed with the software installed on the Arduino. The Arduino is programmed to determine the proportions of each of the primary colors sensed by the CdS. The proportions of the primary colors can then be used to vaguely infer the color of the sample. Precise measurement of color isn't required. As discussed the detector must only need to be able to differentiate between a positive and negative result for coliforms in the water sample. A positive test will produce a color change that will be differentiable by the sensor from a negative test.

Earlier it was mentioned that the transparency of water could pose challenges for detection. Two different detection setups will need to be tested in order to determine which method provides the most accurate results. The preferred method is for the LED and CdS to be positioned side by side viewing the water sample from above. This method is preferred because it simplifies the overall design from a wiring and compactness standpoint. This method is potentially susceptible to having too much light be transmitted through the sample to collect enough light to accurately analyze.

The alternative method would be to position the CdS photocell opposite of the LED. This method would gather more of the transmitted light but it would be in direct view of the LED. If the LED light is too intense, there might not be enough absorption to remove the light before hitting the detector. This would mean the detector would be picking up light directly from the LED as opposed to measuring the light coming from the water. It's possible that either method could be satisfactory due to the non-precise nature of the method in which case the more compact first method would be chosen.

5.4.5 Optical Sensing Wiring and Circuit

The Optical Sensing circuit is very simple and is broken into two parts. The first part governs the operation of the LED. The LED has its red, green and blue leads connected to pins 2, 3 and 4 respectively and has a common anode connected to a 220 ohm resistor leading to the ground. 220 ohms is a common value to use as a current limiting resistor for an LED, connecting an LED to the arduino board without a current limiting resistor will draw too much current from the board and potentially damage it. The resistor limits the current in the LED as well preserving its lifetime, without a current limiting resistor the LED would burn out too quickly, causing inconsistent results over time without regular recalibration of the sensor. This configuration also allows each of the individual LEDs within the package to be turned on and off individually. The other part of the circuit governs the photocell. The CdS photocell is fed 5V from the arduino microcontroller. The other lead of the photocell is connected to a 10k ohm resistor that connects to the ground, effectively creating a voltage divider. This allows the microcontroller to read a changing analog value from the node. The voltage at this node is what allows the processor to determine the color of the sample. The response of the photocell varies with color and therefore the voltage at the analog input changes with color. A diagram of the LED and sensor circuit is shown below in figure 21.

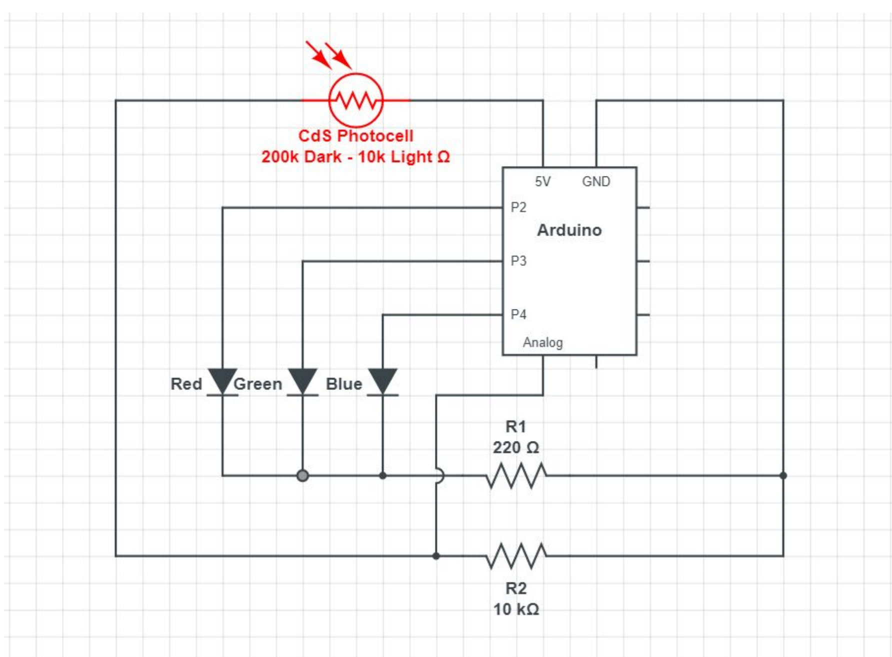

Figure 21: Schematic of the Color Sensor and RGB LED configuration.

6.0 Hardware Design

To ensure the prototyping of the PUVC can go as smoothly as possible during the unusual circumstances of the build the team had to extensively preplan essential component design. This section will cover our planned designs as well as the prototypes for each part of the PUVC that we have deemed essential to plan for. This section will cover all devices that control the water movement, sanitation, water analysis, control devices, user interface and power systems. The section will also contain data and schematics pertaining to our build as best as we can predict. Many of these designs may change as a result of additional testing but as of now these designs represent the teams current understanding of our problem statements and potential real world solutions to these problems. These designs will not focus on optical manipulation or considerations and will focus on the physical design such as lens mounts, placements, and housing units for the LEDs.

6.1 Pump Array Design and Fitler

To move water throughout the system a design for a pump array must be put into place. The main design considerations are rate of water, water pressure, water level monitoring. To achieve a robust system that allows for water to be moved to all essential components three pumps will be required. The first pump will be the input pump into the tank. This pump will be a slightly higher power than the other two as it will have to fill the tank at a reasonably fast rate. AS mentioned in section three a final pump has been selected but further testing must be done before each pump can be guaranteed to function correctly. The second pump needed for the system will be a small pump to move water from the sanitation tank into the small analysis tank. This pump can be of much lower power as a fraction of the amount of water must be moved. Three will also have to be in place electronic controls to switch the pumps off once the water monitors are tripped. The water monitors will be placed within the large sanitation tank and also within the analysis tank to ensure the pumps do not cause overflow and damage to the unit. The final pump installed in the system is an optional pump that can be used to move water from the sanitation tank to an outside source such as a reservoir tank. This pump can be set to whatever specifications the end user would like.

The filter in the system will be an important feature. To ensure that the PUVC does not become overly expensive purely through the filter there will be a preset procedure to the operation. The PUVC will need to have the water it is going to sanitize be clear of any objects ¼ inch in size or greater. This can easily be done through a metal screen or shirt. Once the water has been pre prepared then the input hose of the PUVC can be inserted into the water and the pumping will begin. The fitler will be a pre-purchased filter rated to remove small particulate, heavy metals, and provide an initial slight germicidal effect. The removal of these particulates will also allow the UVC to penetrate into the water deeper and allow for more coliform to be exposed to the radiation. Depending on the severity of the water contamination this filter will be replacedable with a higher quality one purchased from another retailer. In conclusion the filter will serve as the initial barrier to coliform as well as purify the water for the UVC to take max effect.

6.1.1 Pump Connections

The pump connections will allow the water to move through the system. There will be three main hose lengths to connect the unit. The first hose length will connect the sanitation tank to the filter, high power initial array and the water sources. This hose will be made of a plastic meshed material and be ½ inch in diameter to allow for a larger amount of water to flow. The second hose will connect the analysis unit to the sanitation tank. This line will be smaller, most likely ⅛ inch in size. This smaller size is needed to ensure that too much water does not flow into the analysis tank and overflow it causing damage. The third hose will allow for water to flow out of the sanitation tank once the negative coliform test is confirmed. This hose will be optional as the water will flow freely if needed from the connector housed in the sanitation tank. This hose connection could also allow for the PUVC to be connected to a larger system. The hose could also be varied in size to allow a faster emptying of the tank. In summation the hose connections will allow water to effectively flow between the tanks and also allow the PUVC to be connected to many larger water processing or holding units.

6.1.2 Water Level Monitoring

For the pumps to operate correctly the PUVC must be able to stop itself from potentially overfilling. To ensure that this will not occur the PUVC will employ a small water monitoring device placed at specific points within the sanitation and analysis tank to turn off the pump before the units overfill. The device we will use to do this will be an analog TDS sensor that operates on a simple conductive circuit. The circuit is as simple as an open circuit of two wires that when dipped into water close and turn off the pumps. Testing will need to be done to ensure proper operation but with a few tests a final spot for the switches will be chosen. The switches have been purchased but are pending testing, as a backup the team is also looking at float switches as an alternative measure if the conductive circuit does not work. The floating switch is a closed switch that is connected to a buoyant end. When the buoyant end rises the circuit is broken and the tank pump will turn off.

6.2 Fill Tank

For the PUVC to be most effective the input pump must be connected through a hose to a reservoir or laid into a body of water. The fill tank will be used as a preprocessing tank. As mentioned earlier to ensure that the UV is most effective we need to eliminate any matter within the water that would absorb or reflect the UV rays. Due to our UVC lamp/leds operating at a central wavelength of 254 nanometers we need to ensure that many small particulate and heavy metals are not present in the water to maximize penetration. The fill tank will also serve as the area where water is prepared to go into the PUVC. The fill tank will not be included in the physical design but will be in the procedure of using the PUVC. For best operation the PUVC should be connected to a lightly filtered reservoir of water.

6.3 High Power LED Pre Processing

The high power LED ring provided several unique engineering problems. The most important of those is how would the design be able to defend the LED's from the water while also allowing for effective sanitation powers. To tackle these problems two designs are being put forth as potential solutions. Both will consist of 10 of the E275-3 LED's but will have different orientations employed. The first design presented is a flat array design and the second is a circular array design. The arrays will each have different power distributions based on the orientation of the LEDs. As the design process progressed though it soon became apparent the most cost efficient array would be a float rectangular array. The following sections will review the hardware and housing of the LED high power array.

6.3.1 Flat Array Mechanical Design

The flat array was the first design decided upon by the team for the high power array. The flat array proved not to be the most effective solution to delivering peak power to the water without sacrificing extra machining expense. Also as shown below in figure 22 the distributor of the LEDs we were purchasing had a board of 5 LEDs for sale. This unit is easily integrated into the design as opposed to wiring each individually.

Figure 22: Photo of the LED panel purchased to be used in the linear array (Reprinted with permission from ILT)

As mentioned earlier there has been great delay in the ability to get electronics and test them. Due to this we would like the reader to keep in mind that the designs presented below in figure 23 and 24 are subject to change and the mockups are simple CAD representations of the final prototype. Shown in the design below is the simple flat LED array. As can be seen there is an entrance hole tapered down to 1/4 inch to match the input hose with an adapter to increase the water pressure. Then the water will enter a square array that is 10 mm high by 20 mm wide and be passed through the array of LEDs. Shown in figure 23 is how the unit will be assembled. The screws have been left out to simplify the diagram. The unit will be made of an acrylic or plastic material that is non transparent to UVC. there will be a small gap on both sides to fit the UV fused silica window mentioned in section 3. This window will be glued in place. Once the window is in place the LEDs and their wires will be lowered into a housing and covered with a thin aluminum lid.

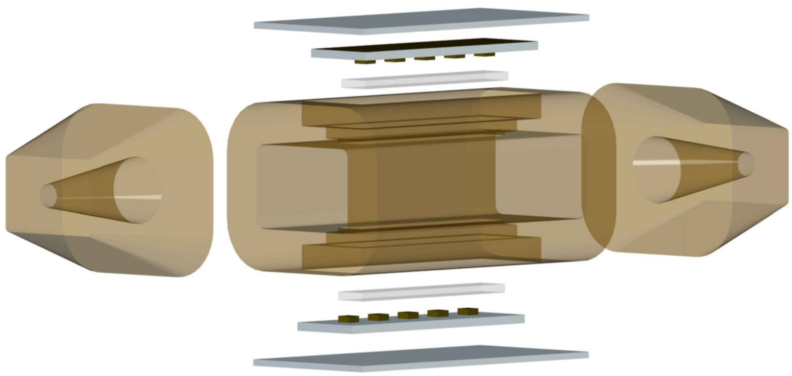

Figure 23: Autocad Rendering of high power LED array side view 3D

Shown below in figure 24 is the same flat array but a two dimensional view. This was included to again show simply how the unit will be assembled and how each part will fit together.

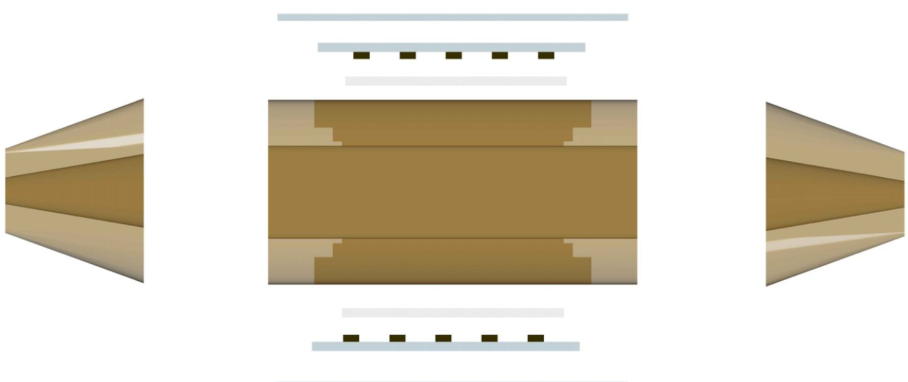

Figure 24: Autocad rendering of high power LED array 2D

Upon testing the square array the team found many problems within the design. The first problem was that as water traveled through the array the water would become very turbid. This meant that there were many pockets of air and turbulence within the water as it travelled through the array. This turbidity reduces the overall penetration of the UVC light and therefore had to be eliminated. As a solution to this the team redesigned the array to be circular in nature. Shown below in figure 25 is the circular array the team ended up using in the final prototype.

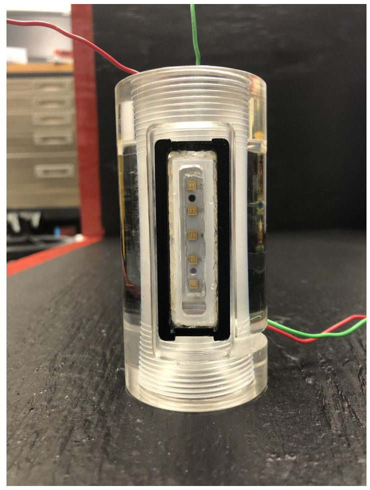

Figure 25: Prototype circular array used in final PUVC design

This circular design when installed vertically allows the water to flow in evenly and not create any excess turbidity. This allows for a more even refractive index within the water that maximizes the penetration power of the LEDs. As can be seen in figure 25 above the design also employs the parallel LED panels. This again maximizes the power that can be delivered into the water, and ensures an even distribution. Further discussion of testing of the array, its power delivered, and how much UVC dose is delivered can be found in section 8.

6.4 Processing Tank

The processing tank will be used as an additional cleaning unit as well as an ambient cleaner while the analysis is performed. The processing tank will contain an array of four LEDs focused into an elliptical beam to increase the UV dose. A more detailed representation of the lens matrix can be found in section 6. These UV diodes will provide an additional UVC cleaning effect as well as prevent any ambient coliform from reproducing effectively. The diodes will be secured in place with 3D printed mounts and then glued into place. The team is still testing whether it would be most effective to place the LEDs within the water and protect them or simply have them radiate the water from above. Once this is decided the UVC diodes will be placed permanently and then sensitive electronics will be covered in a water resistant epoxy. These LEDs will be placed within the 10 gallon holding tank and then again tested for their function. If the LEDs were completely submerged additional steps would have to be taken such as installation of another silica window. The team has prepared several designs and has begun building the first tank for testing. The first attempt will be a square 1 gallon tank to test all necessary components. Once this is achieved the team will then scale up.

The tank will also contain a small fan to circulate the water through the tank. This is necessary because the UV LEDs will not be focused into the entire tank as mentioned earlier. The fan will circulate the water around the tank allowing it to over time all be exposed to UV radiation. This fan will also assist in emptying the tank when water output is allowed. The tank will also in addition contain a UVC lamp for use when more intensive UVC output is needed. This lamp will be placed in the center of the tank for maximum water exposure and will be protected by a quartz sheath. The SLRU lamp used and its output characteristics can be found in section 3 and 5. In conclusion the processing tank will be the central cleaning unit of the PUVC and allow for multiple coliform contamination severities to be sanitised.

6.5 Analysis Tank

The analysis tank will perform a color analysis test on the water sample that has been treated with the coliform testing reagent. The sample will be illuminated by the LED lighted viewed with a CdS photocell. Figure 26 below shows in an inside view of the tank.

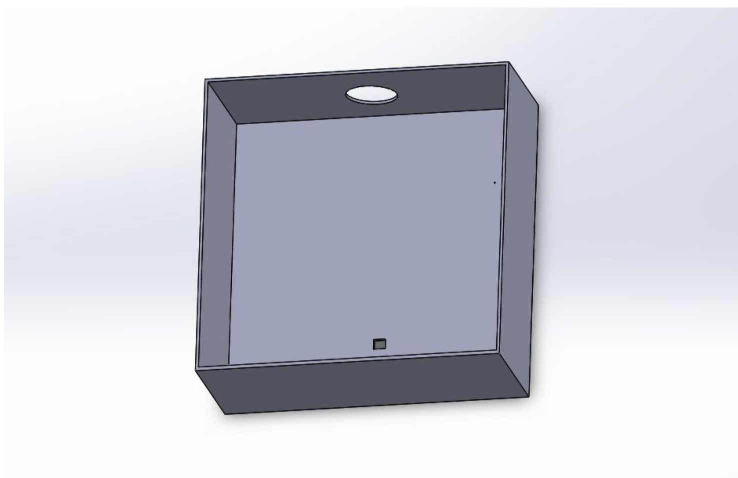

Figure 26: Bottom Inside View of PUVC Water Analysis Tank

There is a circular hole where a hose from the main tank would connect to pull a sample for analysis. There is also a square shaped window in the bottom of the figure, this is for the CdS photocell. Part of the testing and prototyping process is determining whether the CdS photocell should view the reflected light or transmitted light from the water sample. If viewing the transmitted light turns out to provide more accurate results, this window will be the chosen location of the CdS photocell. This section of the tank can hold 1350mL of water when filled to capacity. The optimal water level will be determined through testing based on the optimal optical path length for the optical setup to deliver the most accurate and consistent results. In order to carefully choose the water level in the tank the hose should have a valve on it that lets water into the tank slowly. The next figure 27 shows the top layer and housing for the Arduino microcontroller. In order to protect the electronics it sealed off from the rest of the tank but for a small circular window positioned directly above the CdS photocell window.

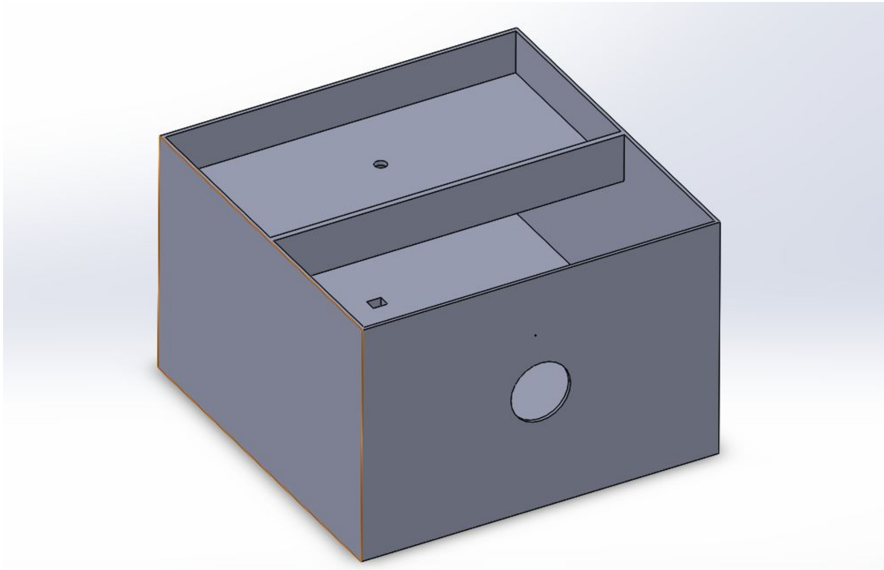

Figure 27: Full Inside View of PUVC Water Analysis Tank

The circular window will house the LED connected directly to the microcontroller in the housing. The window will be large enough to house the CdS as well, should the testing show that the optical analysis system works best when the CdS views the reflected LED off the water sample. There is an opening when the lid is removed to allow for the reagent to be added before the water sample is introduced. The housing for the arduino has sufficient space to store a battery to power the microcontroller for portable use. Figure 28 below shows the complete view of the analysis tank. This has a tight fitting lid to seal the tank from outside air which is required for the coliform testing. There is also a highlighted panel that would be removable to insert batteries, optics, and the microcontroller. There will be a 5V DC to DC converter that can power the microcontroller. That can connect to the microcontroller through the panel as well.

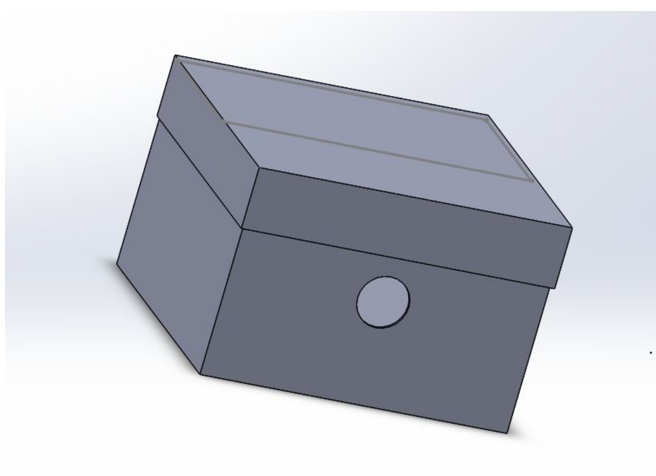

Figure 28: Bottom Inside View of PUVC Water Analysis Tank

6.6 Microcontroller

There are plenty of microcontrollers on the market, each carrying their own benefits and disadvantages. This section will focus on comparing and contrasting various MCU to identify the most efficient from a cost and performance basis. The comparisons will be based off of the designated requirements and intended use for the MCU. Prior to the discussion, all Arduino MCU's are restricted for various reasons and will be omitted onward.

First, as described the MCU must be able to accomplish a myriad of tasks. The most important being the ability to power an LCD screen which will contain the graphical user interface (GUI), which will then be attached to the system. The GUI will be populated using data from sensors, and therefore will need to simultaneously be required to read the sensor values: specifically, the camera to monitor the water. The MCU will also be involved in the verification of the cleaning utilizing the method stated above in section 5.3.

The ESP modules, specifically the 8266 and 32, are quite popular among the Internet of Things realm. They offer an integrated WiFi chip which is easy to program to connect. These chips are offered in a variety of packages with extra IO pins for more functionality. Table 12 below shows a comparison of various ESP modules.

Table 12: Comparison of ESP modules

Feature(s)	ESP8266	ESP32
Processor	32-bit @ 80Mhz	32-bit @ 160Mhz
Bluetooth Enabled	No	Yes
SPI	2	4
I2C	1	2
ADC	1 (10-bit)	18 (12-bit)
Low Power Consumption	20µA	10µA

Both modules offer many of the same features, however, the ESP32 manages to beat out the ESP8266 in the majority of the specifications. Although this is seen, it is to be understood that the 8266 module is older than the 32, and therefore these specifications of the latter should be superior. With that said, the 8266 is cheaper which is where it shines. Both models can be programmed using the Arduino IDE, making the environment relatively simple.

The Raspberry Pi is also well known for its DIY and IoT projects. The Raspberry Pi does offer a significant amount of functionality with respect to the ESP modules. However, this does come with a larger price tag. As of now the most popular models are the Raspberry Pi 3b+ and Raspberry Pi 4. Similar to the comparison of the ESP modules, both Pi models offer similar features with the Pi 4 being more up to date. Table 13 below shows comparison of raspberry pi technical data (2, 3).

Table 13: Raspberry Pi Comparisons

Feature(s)	**Pi 3b+**	**Pi 4**
Processor	64-bit @ 1.4GHz	64-bit @ 1.5GHz
GPIO	40	40
RAM	1GB	1GB, 2GB, 4GB
WiFi/Bluetooth Enabled	Yes	Yes
Gigabit Ethernet	Yes	Yes
Current when Idle	400mA	575mA

Table 13: Raspberry Pi Comparisons cont.

I/O	**Pi 3b+**	**Pi 4**
HDMI	1	2 (Micro)
USB 3.0	0	2
USB 2.0	4	2
Ethernet	1	1
Micro SD Card	1	1

Both the Pi 3b+ and the Pi 4 offer similar specifications with the Pi 4 being slightly upgraded. They have similar port offerings, with the latter having USB 3.0 included.

The most notable thing about the Pi is the ability to run a full-scale operating system, raspbian. This gives a significant amount of flexibility with programming, allowing access to an expansive list of libraries and tools to be used: this includes GUI libraries and many more which will be talked about in section 7. There are also a significant amount of GPIO pins which increase the amount of flexibility with sensors and things alike. With that, the number of moving parts may increase the complexity compared to the barebones ESP modules, leaving more room for error. The increase in flexibility and opportunity is accompanied by an increase in price, however, there are plenty of ways to combat this, the main focuses on purchasing an off-brand, like Le Potato, or another MCU like the BeagleBone Black.

6.7 DC Power system

The PUVC will have the ability to be powered either through a battery or wall outlet. The batteries will be rechargeable with the option of charging via either solar panel or by the wall outlet. Charging the batteries will require charge controllers to avoid damaging the battery. A PWM charge controller will be used for solar charging as well as a charger circuit for charging from a wall outlet AC source. These two charge controllers will be connected in parallel to the battery bank. DC-DC converters will also be required since each electronic component's voltage and current ratings won't necessarily match each other or that of the battery. DC-DC converters will also act as voltage regulators to ensure the safe and optimal operation of each electronic component. These converters will be designed using Texas Instruments' Webench tool and then exported to EagleCAD where the PCB and build of material's list will be produced. The first step in designing a power system is to list out the power requirements of all devices as in table 14 below. The solar charge controller for charging the battery through the solar panels will be purchased. A charge controller for charging through the AC power source will need to be designed to prolong the battery's cycle life and for safety reasons as well.

Table 14: List of parts and their power consumption

Part	Rated Voltage	Max current	Quantity of part	Power consumption
Decdeal Water pump	12 V	416 mA	3	14.98 W
E275-3-S LEDs	6 V	50 mA	5	0.3 W
Raspberry Pi 3B	5.1 V	1.2 A	1	6.12 W
Arduino microcontroller	5.1 V	500 mA	1	2.55 W

The differences in voltage of the components in table 14 of the components of the PUVC necessitate the design of a DC-DC converter to match their voltages. The total power consumption will also be used to determine what battery will power the PUVC and the charge life of the system. Table 15 below identifies the components in the system which are powered by the microcontroller. The power rating of these devices already account for the power consumption by these devices so there is no need to connect them to the main power source nor to DC-DC converters. They will simply connect to the appropriate pins of the microcontrollers.

Table 15: Secondary components and their power sources

Part	Power source
RGB LED	Arduino microcontroller
BMP280	Raspberry Pi 3B
Arducam 5	Raspberry Pi 3B
Video Camera Module for Raspberry Pi	Raspberry Pi 3B

Figure 29 below gives an overview of the power system and the powers system as well as the power system output, that is, the components which run directly off of the power system via the output end of the DC-DC converters.

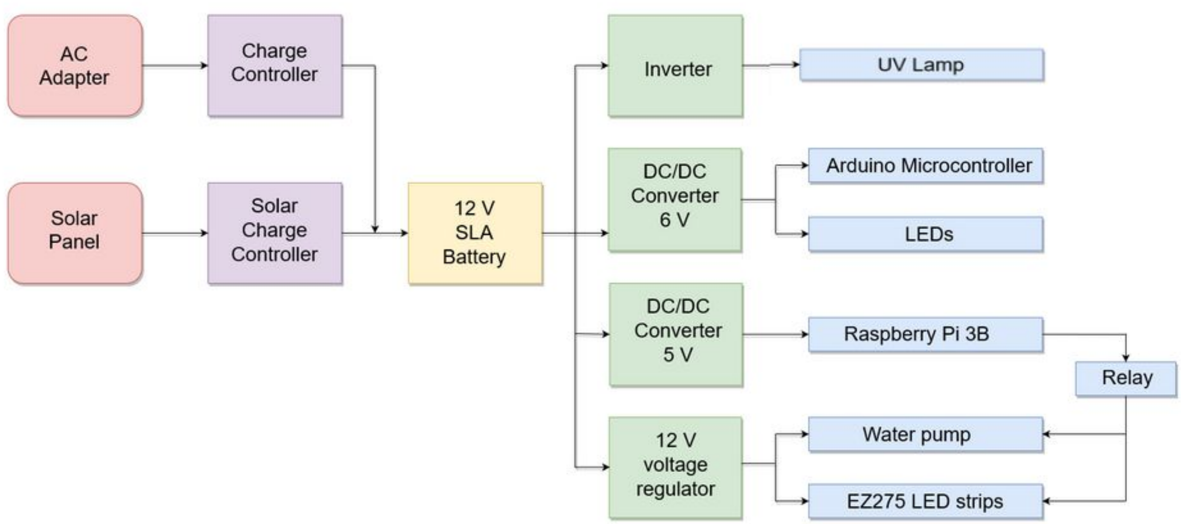

Figure 29: Overview of Power System Layout

6.7.1 Battery selection

It was determined that the best suited battery for this project would be either a Lithium Polymer or Lithium Ion batteries based on the research outlined in section 3.2.9. These batteries have high energy densities and high power densities which marks the capacity of the battery. The first step in selecting a battery to power the PUVC was creating a power budget in order to clearly establish how much battery capacity is needed for the project. Due to the lack of access to labs for testing of the electronic parts, very rough estimations will be used to determine the necessary battery capacity. We expect that we may have to reevaluate these calculations in the future.

The current consumption of the electronic components of the PUVC were assumed to not be the max current rating of each device. Instead a current consumption of 80% of the max current consumption of the water was assumed. The duty cycles of each component is shown in table 16 below. The duty cycles were based on estimations. For example it was assumed that the water pump would be off for most of the time since the water pumps will be idle during sanitization of the water once the water is pumped into the cleaning tank so it was given a conservative estimated duty cycle of 30%. Table 16 below shows the electronics and their current draws.

Table 16: Current draw estimations of each component

Part	Average Current	Duty Cycle	Estimated Current Draw
2 Decdeal Water pumps	1 A	30%	300 mA
5 E275-3-S LEDs	250 mA	95%	238 mA
1 Raspberry Pi 3B	960 mA	100%	960 mA
1 Arduino microcontroller	400 mA	100%	960 mA

The estimated current consumption is listed in table above. Summing up these estimated current draws, the total current draw was estimated to be about 2.5 Amps. Accounting for the power loss of the system a 20% margin of error was added to this calculation. With the system loss factored into the calculation hte capacity for one hour of operation is 3 Amps. As listed in the engineering requirements specification, the PUVC should be able to run for a minimum of 4 operating hours per charge. This means a battery capacity of 12 Ah is required.

With such a high battery capacity requirement the battery options are limited. Initially, Lithium ion and lithium polymer batteries were desired because of their high power and energy densities and their prevalence in modern technology. However it was found that lithium battery cells generally do not go beyond a capacity of 2500 mAh. We considered connecting a few 18650 LiPo cells in parallel but after doing some research it was found that it comes with a high safety risk. The cells would need to be very closely matched and small differences such as the differences that exist in the charging and discharging current between them can cause issues. If one cell were to fail, the other cells would dump all their charge into the failing cell. Some packs such as the Turnigy 5000mAh 4S1P 14.8V 20C Hardcase Pack go beyond this capacity by internal combination of cells but aside from being expensive these battery packs have two sets of wires - the main wire for charging and discharging of the battery and a balancing plug for equalizing the charging of the cell. The battery packs require expensive chargers to be charged as intended. This extra balancing wire set would also further complicate the circuitry connected to the battery. USB power banks were considered but they are rather expensive and would need modifications to be made compatible with all of the electronic parts of the system. It was preferred not to use USB cables to connect all the electronic components together.

Next, lead acid batteries were considered since they are cheap and they have a high energy density . They are also often used in solar panel systems so there is a lot of information available for reference on the web. The downside to lead acid batteries is that they have a low energy density, they have a slow recharge time and they are large and heavy. It was ultimately decided that a lead acid battery would be used to power the PUVC. The fact that they are large and heavy goes against the portability aspect of the PUVC but will still allow the project to be kept within the portability specifications outlined in the requirement and specifications section of this document. The sealed lead acid battery was one of few viable options for minimizing the cost of the PUVC which is necessary since the budget is limited as this project is being funded by the members of the group. The ExpertPower 12V 12Ah Sealed Lead Acid battery will be used for the battery bank of the PUVC. It is a 3.45 lb battery with F2 type terminal. This battery was chosen because the Ah capacity requirement estimation is exactly met with this battery. Figure 29 below shows the ExpertPower 12V battery.

6.7.1.1 Five Volt DC/DC converter

Since we have multiple electronic devices which have varying voltage requirements, DC to DC converters will be essential to the PUVC. The main power supply will need to be buckled down to a regulated 5.1 V for the Raspberry Pi, 6 V for the LEDs and a voltage regulator will be needed to output a steady 12 V for the water pumps to suit all the needs of the different electronic devices. The solar charge controller selected for this project already has an integrated 12 V regulator so only a 5.1 V and 6 V regulator need to be designed. TI Webench power designer will be used for the design of these DC to DC converters. The design will be selected on factors such as efficiency, cost and footprint size to best match the requirements of the PUVC. These designs will then be exported to EasyEDA and developed into a PCB along with all other schematics required for the PUVC. The parameters put into Webench power designer for the 5 V DC-DC converter is shown in table 17 below.

Table 17: Webench power design parameters for 5 V DC-DC converter

Design Parameter	Value
Vin Min	10.8 V
Vin Max	14.4 V
Vout	5.1 V
Iout Max	2 A

Since no datasheet or information about the voltage range of the selected 12 V battery could be found they were calculated based on the nominal voltage range of a lead-acid battery cell. The nominal voltage of a lead acid cell is 1.8 V when fully discharged. Since the 12 V battery consists of 6 cells Vin Min was set to 10.8 V and V Max was set to 14.4 V which is the maximum voltage of a fully charged 12 V lead acid battery. Iout max was set to 2 A which is close to the combined max currents of the microcontrollers. Vout was set to the voltage rating which is 5.1 V for the Raspberry pi. The designs provided by the power designer are shown in table 18 below.

Table 18: Comparison of 5V DC/DC converters form Webench

Basic Details	TPS563249	TPS563200	TPS56628DDAR
BOM area	157 mm^2	165 mm^2	174 mm^2
BOM cost	$1.09	$1.00	$1.19
BOM count	9	9	11
Efficiency	91.7%	94.3%	94.6%
Frequency	1.43 MHz	796.72 kHz	766.24 kHz
Topology	Buck	Buck	Buck

The TPS56628DDAR was chosen simply because it has the highest efficiency and is only marginally more expensive than the other designs. Its 174 mm^2 BOM area is still quite small. The frequency of the converter is inconsequential for the purposes of this design. The schematic of this design is how in Figure 30 below.

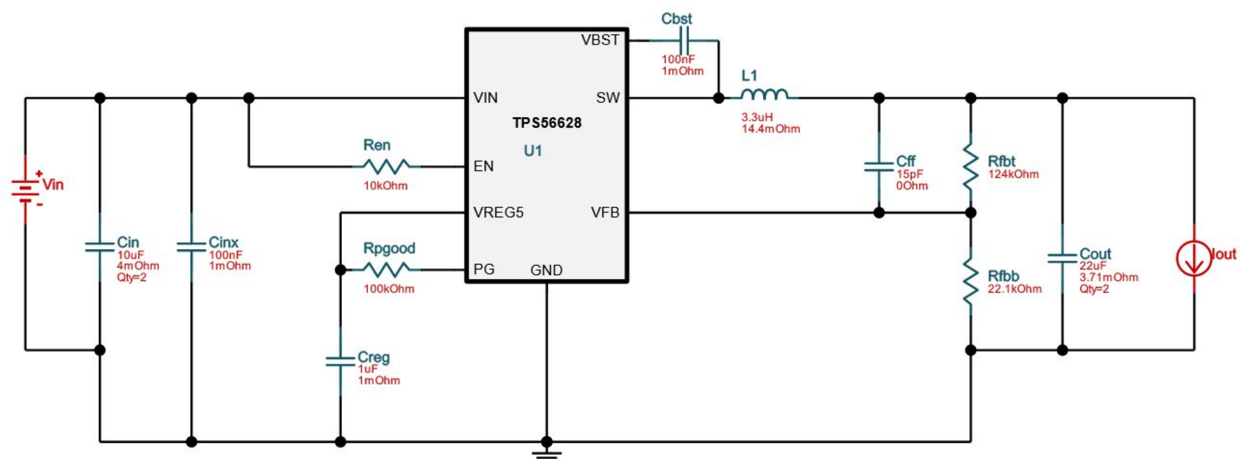

Figure 30 : Schematic of 5.1 V at 2 A output DC to DC converter designed in TI Webench

The Bill of Materials list of this schematic is shown in table 19 on the next page. Parts were chosen to be purchased as cheaply as possible.

Table 19: Bill of Materials of 5.1 V DC-DC converter

Part	Manufacturer	Part Number	Quantity	Price ($)	Footprint (mm^2)	Description
Cff	Kemet	C0603C150M8GACTU	1	0.01	4.68	Cap: 15 pF Package: 0603
Cbst	Kemet	C0603C104Z3VACTU	1	0.01	4.68	Cap: 100 nF Package: 0603
Cin	MuRata	GRM21BR61E106MA73L	2	0.05	6.75	Cap: 10 µF Package: 0805
Cinx	Kemet	C0603C104Z3VACTU	1	0.01	4.68	Cap: 100 nF Package: 0603
Cout	TDK	C1608X5R1A226M080AC	2	0.12	4.68	Cap: 22 µF Package: 0603
Creg	Kemet	C0603C105Z8VACTU	1	0.01	4.68	Cap: 1 µF Package: 0603
L1	Vishay-Dale	IHLP4040DZER3R3M01	1	0.65	166.05	L: 3.3 µH
Ren	Yageo	RC0201FR-0710KL	1	0.01	2.08	Resistance: 10 kΩ
Rfbb	Vishay-Dale	CRCW040222K1FKED	1	0.01	3	Resistance: 22.1 kΩ
Rfbt	Vishay-Dale	CRCW0402124KFKED	1	0.01	3	Resistance: 124 kΩ
Rpgood	Vishay-Dale	CRCW0402100KFKED	1	0.01	3	Resistance: 100 kΩ
U1	Texas Instruments	TPS56628DDAR	1	0.6	55.2	Buck converter

6.7.1.2 Six V buck converter

A DC-DC converter in the form of a buck regulator is also needed for some of the UV LEDs which have a voltage rating of 6 V. The process for designing this voltage regulator is the same as that of the 5 V DC/DC converter. We used TI Webench power designer once again with the input parameters shown in table 20 on the next page.

Table 20: Webench power design parameters for 6 V DC-DC converter

Design Parameter	Value
Vin Min	10.8 V
Vin Max	14.4 V
Vout	6 V
Iout Max	1 A

TI Webench provided the following designs which were then compared to determine the best suited converter. The comparison of characteristics are shown in table 21 below. After comparing these 6 V DC/DC converters the TPS561208 was selected due to the fact that it has the highest efficiency of the three, it has the lowest BOM count and it is only $0.04 more expensive than the three converters considered for the design.

Table 21: Comparison of 6V DC/DC converters form Webench

Basic Details	**TPS561208**	**TPS562202**	**TPS563240**
BOM area	74 mm^2	114 mm^2	163 mm^2
BOM cost	$0.82	$0.78	$0.86
BOM count	8	11	10
Efficiency	94.6%	94.5%	91.8%
Frequency	538.5 kHz	569.67 kHz	1.37 MHzBuck
Topology	Buck	Buck	Buck

TI Webench power designer also provided the schematic with the component values already calculated to meet the design parameters. The 6 V buck converter schematic is shown in figure 31 on the next page.

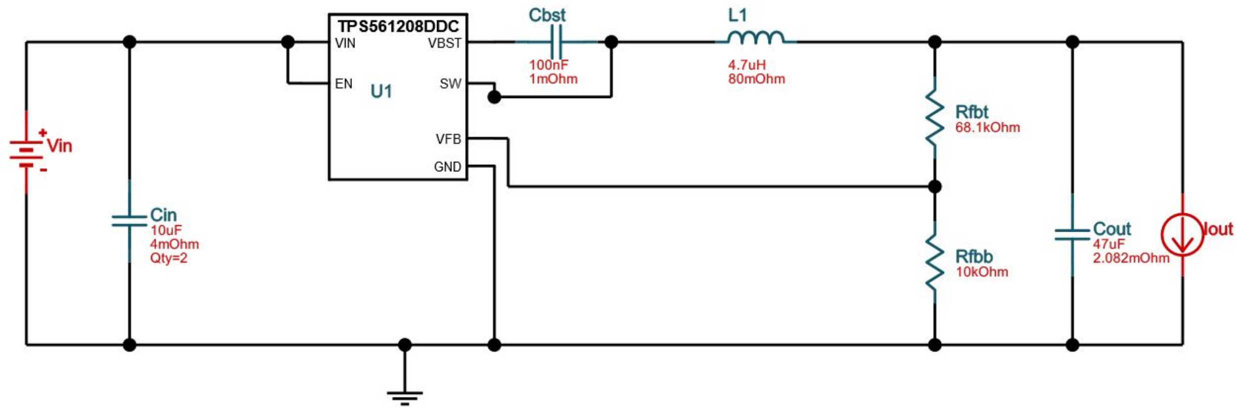

Figure 31 : Schematic of 6 V at 1 A output DC to DC converter designed in TI Webench

The bill of material was also provided by TI Webench power designer. Table 22 below shows the bill of material for the 6 V DC-DC converter.

Table 22: Bill of Materials of 6 V DC-DC converter

Part	Manufacturer	Part Number	Quantity	Price ($)	Footprint (mm²)	Description
Cbst	Kemet	C0603C104Z3VACTU	1	0.01	4.68	Cap: 100 nF Package: 0603
Cin	MuRata	GRM21BR61E106MA73L	2	0.05	6.75	Cap: 10 µF Package: 0805
Cout	TDK	C3216X5R1E476M160AC	1	0.39	10.92	Cap: 47 µF Package: 1206
L1	NIC Components	NPI43C4R7MTRF	1	0.1372	30.74	L: 4.7 µH IDC: 1.9 A
Rfbb	Yageo	RC0201FR-0710KL	1	0.01	2.08	Resistance: 10 kΩ
U1	Texas Instruments	TPS561208DDCR	1	0.158	10.47	Buck converter
Rfbt	Yageo	RC0201FR-7D68K1L	1	0.01	2.08	Resistance: 68.1 kΩ

6.7.1.3 ATmega328 microcontroller PCB

The microcontroller used for reagent color sensing is the ATmega328P-PU. Once the color reading was tested and working on the arduino development board, a PCB which integrates the microcontroller and its connected components was designed. Using the open source schematics of the arduino, all components of the arduino being used for color sensing were included on the PCB and the unused components removed. The PCB includes a socket for the ATmega328P microcontroller, a 16MHz crystal oscillator, an RGB LED, a Cds photocell, some resistors and some capacitors. The board also has jumpers for the UART transmit and receive pins, the 5 V pin and the ground pin. These jumpers were made available so that the arduino could transmit its results to the Raspberry Pi via UART communication which is then used to determine whether the cleaning process was successful or not. The PCB design was done using EasyEDA and the PCB was printed by JLCPCB. The ATmega328 has 28 pins so a 28 pin socket was included on the PCB. The ATmega was programmed through an arduino board and then the chip was removed from the arduino board and inserted into the socket of the designed PCB. The PCB also includes a 7805 linear regulator to convert the 12 V from the solar charge controller to 5 V which is the voltage rating of the ATmega328 chip. Shown in figure 32 below is the schematic used for the PCB design.

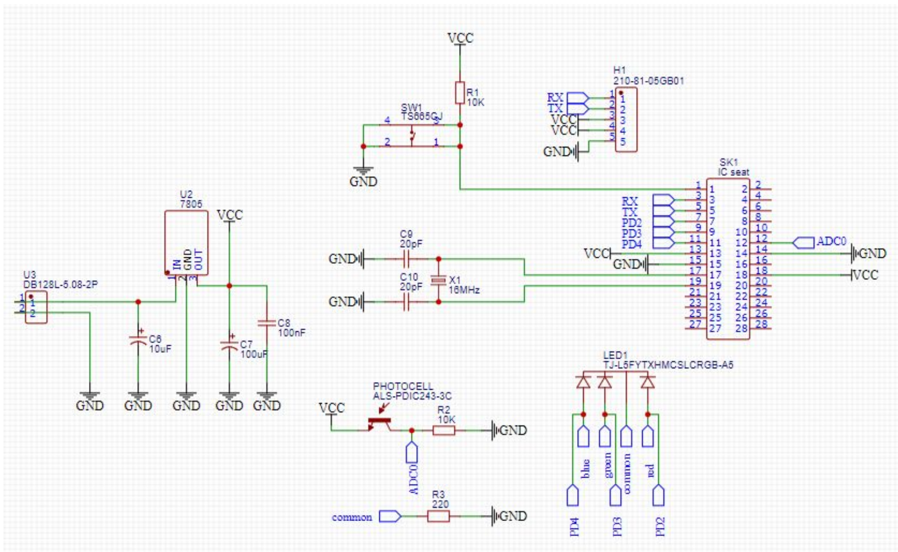

Figure 32: Color sensing PCB schematic designed for ATmega328P-PU microcontroller

A prototype of the circuit was built using a breadboard and jumper wires before the PCB was printed. The prototype is shown in figure 33 below.

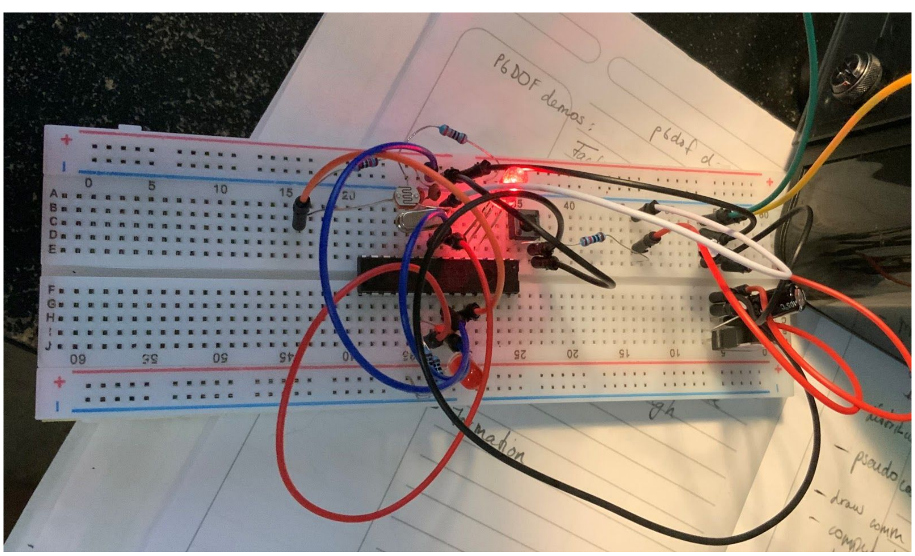

Figure 33: Color sensing prototype created on breadboard

6.7.2 PCB Layout and Design

The next step in designing the DC-DC converters is the printed circuit board design. Aside from a few part changes, the design schematic acquired from TI Webench was followed exactly. While Webench does have a schematic export function this feature was not used since the exported schematic contains generic parts without values and footprints. Instead each part listed in the Webench part list was put into EasyEDA's LCSC search tool in order to acquire the CAD models - both schematic symbol and footprint. For a few components the parts were unavailable from LCSC in which case a replacement part with similar values and characteristics had to be identified. Once all the parts were laid out and connected according to the Webench design, a circuit board file was generated from the schematic. The schematics of the 5 V and 6 V converters are shown in figure 34 and figure 35 respectively.

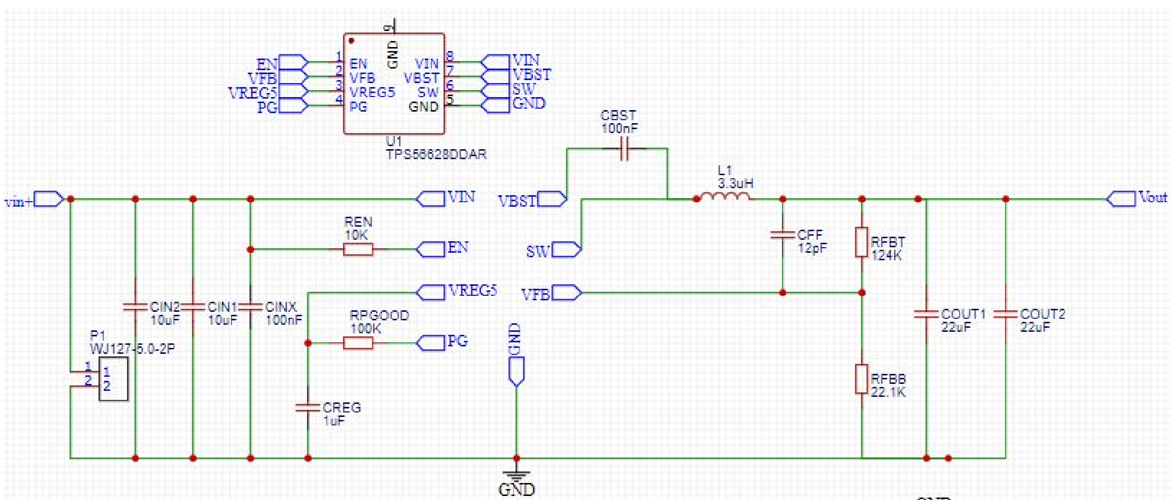

Figure 34: Schematic of 5 V DC-DC converter drawn in EagleCAD

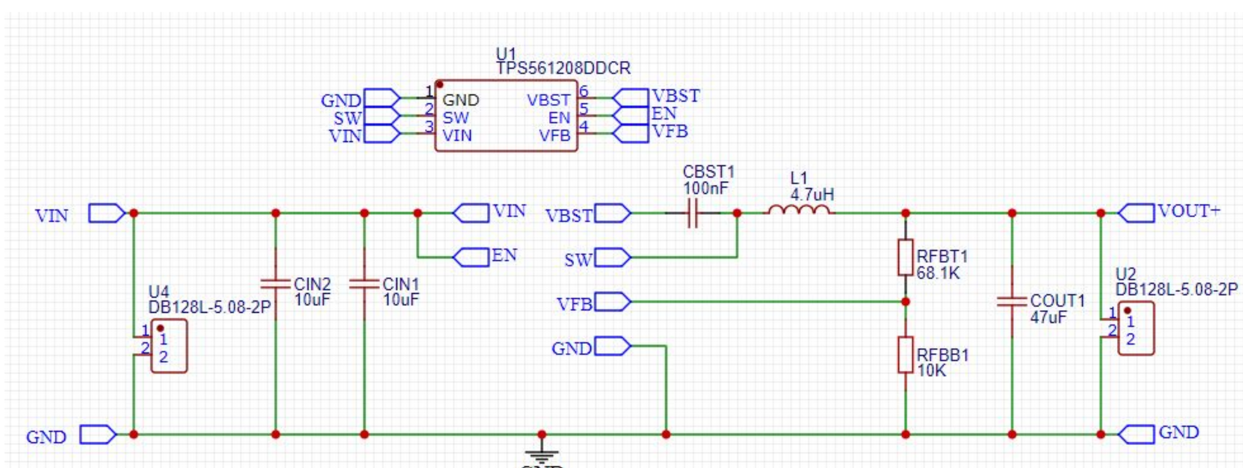

Figure 35: Schematic of 6 V DC-DC converter drawn in EagleCAD

The components were laid out on the board with part location and routing choices made deliberately and carefully. The datasheets of the converters provide PCB layout guidelines which were followed in laying out the components on the PCB. All PCBs were 2 layer boards and the ground nodes were left unrouted. Then, the copper pour tool was used to make a top ground layer on the PCBs. Vias were used for connecting top layer nodes to bottom layer nodes. The trace widths were also calculated to meet the current requirements of the boards. The final PCB layout of the 5 V DC/Dc converter is shown in figure 36 below and the final PCB layout of the 12 V DC/DC converter is shown in figure 37 below.

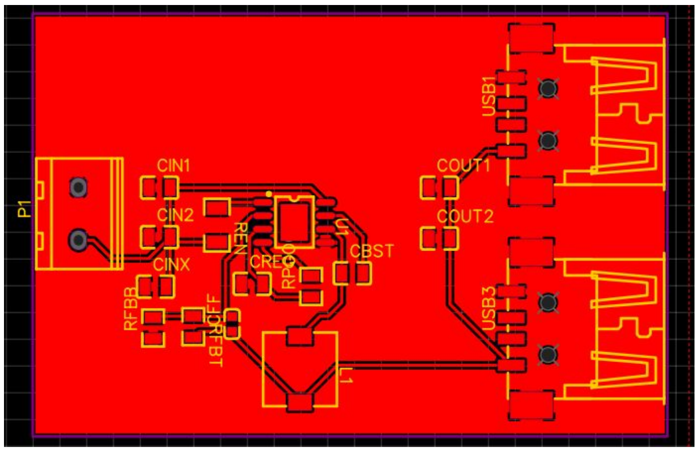

Figure 36: PCB layout of 5 V DC-DC converter

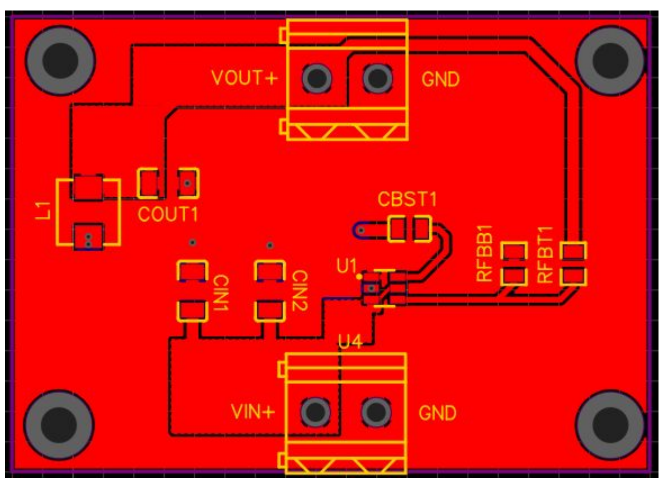

Figure 37: PCB layout of 6 V DC-DC converter

Screw terminals were used for the inputs to all PCBs. The 5 V board has 2 female USB ports connected in parallel at the output of the 5 V converter. An output USB port at the 5 V converter was chosen so that the Raspberry Pi could be powered by connecting a USB cable from the converter to the Raspberry Pi's input microUSB.

The ATmega color sensing PCB was laid out so that the RGB LED and the Cds photocell would be adjacent to each other for optimal color sensing results. The PCB layout of the ATmega328 PCB is shown in figure 38 below.

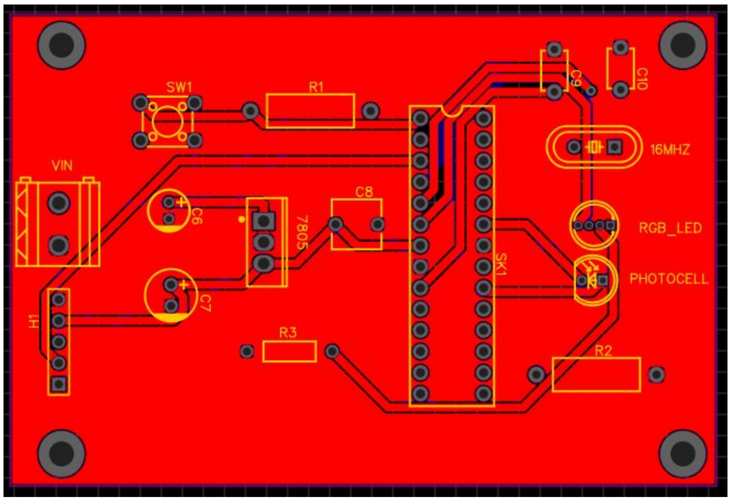

Figure 38: PCB layout of color sensing PCB designed for ATmega328P-PU microcontroller

After testing the DC-DC converter components on the breadboard and verifying that the PCB designs of the converters are properly connected, the PCB schematic will need to be sent to a PCB vendor for printing. A PCB manufacturer with low shipping times was desired. It was decided that the PCB boards would be purchased from JLPCB. This PCB vendor was chosen because they offer 5 circuit boards printed at $2 for 2 layer boards with dimensions below 100mm x 100mm. Both converter PCB designs fall below this dimension. Additionally, JLPCB guarantees that boards will be printed within 24 hours from the time of gerber file upload. The gerber files of the DC/DC converter PCBs will need to be uploaded to JLPCB for printing.

6.7.3 Solar charge controller - BQ24650

We had initially considered using the BQ24650 integrated circuit to regulate both the voltage and the current of the battery during charging. According to the datasheet of the BQ24650 this IC by Texas Instruments has Maximum Power Point Tracking capability with a resistor programmable MPPT setting. It is rated for a 5 V to 28 V input solar panel which is ideal since we intend to use a 12 V solar panel which can output a voltage of up to 17 V under peak conditions. This controller has an accuracy of ±0.5 % charge voltage regulation, ±3 % charge current regulation, and ±0.6 % input voltage regulation which are the most important aspects of a charge controller. Although the BQ24650 is designed specifically for charging Li-ion batteries the design can be modified to accommodate charging of Lead-Acid batteries. The typical application provided by the datasheet requires an integrated thermistor which Lead-Acid batteries typically do not have hence the required modifications. Texas Instruments outlines the schematic needed for charging a sealed lead-acid battery. The schematic for charging a lead acid battery is shown below in figure 39.

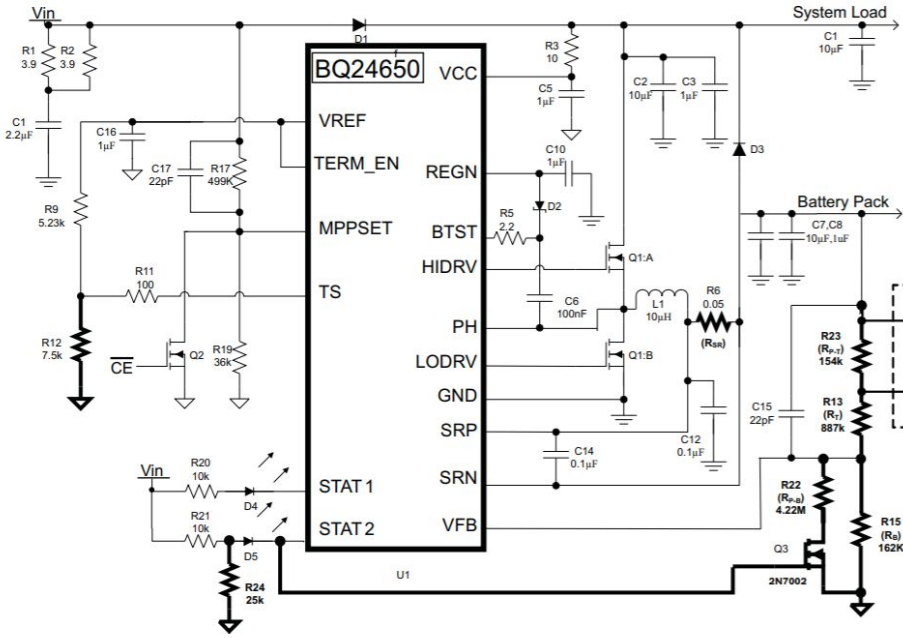

Figure 39: Schematic for pulse charging of a Lead-Acid Battery using the BQ24650 MPPT charge controller by Texas Instruments

This schematic above has functionalities of input voltage regulation, voltage regulation and current regulation but it lacks over discharge protection and short circuit protection. These protections could either be added to the schematic above or there could exist a seperate battery management circuit. We decided to go with the latter option since a battery management circuit will also be needed when the battery is being charged from an AC source. The battery to be used in the PUVC will be a lead acid battery but because lead acid batteries generally do not have integrated thermistors, the charger's over and and under temperature regulations will not be used. This schematic would have to be drawn up in EagleCAD as well as its PCB layout. Due to uncertainty of access to the labs for circuit building and testing a backup solar charge controller was identified. This backup controller will not need to be designed but instead will just be purchased as a final product and is discussed in section 3.3.9.

6.8 Sensors

As stated prior, the Raspberry Pi will be used to monitor the water as well as other environment variables. In doing so, the Pi proved useful, being both power efficient while providing a significant amount of GPIO pins, 40 to be exact, allowing for a very liberal approach when picking sensors. The main measurements that will be needed are temperature, humidity, light intensity, and battery life. With the amount of pins, this can vary to include many more sensors for a more accurate understanding of the environment at large.

First, the temperature sensor. There are a myriad of these sensors offered on the market, each having their own advantage, whether it be price, accuracy, or power consumption. The main ones that will be investigated for temperature measurements are the DSB18B20, DHT22, and the BME280.

The most basic of the three is the DSB18B20 and functions purely as a temperature sensor. The sensor is able to be used properly in the range of -55°C to 125°C (-67°F to 257°F). However, based on the temperature, the accuracy of the sensor will change: within the range of -10°C to 85°C (14°F to 185°F) with ±0.5°C (32.9°F) of accuracy. The suspected use for the device will be within this range, and therefore will suffice. The DSB18B20 has an output resolution of 9-bit to 12-bit and is programmable and has a relatively fast conversion rate of 750ms at the 12-bit output. The Sensor can operate at either the 3V or 5V provided directly from the Pi, with a maximum current of 1.5mA. Provided the simplicity of the component, there are a total of three pins: VCC, Ground, and Data. The data pin is able to communicate via a 1-wire method. This sensor would be most efficient in a smaller system with a limited amount of pins, due to the copious amount of pins of the Pi, this is not a constraint. This being a basic temperature will suffice, however, with further discussion may prove to be the least efficient.

The DHT22 is similar to the DSB18B20 in many aspects, however, one of the key places where it differs is that the DHT22 can function as both a temperature and humidity sensor. The DHT22 has a slightly wider accurate temperature range compared to the DSB18B20, having an accuracy of ±0.5°C (32.9°F) within the operating temperature of -40°C to 80°C (-40°F to 176°F). As mentioned, it is also able to read the humidity and can read anywhere in the 0-100% humidity range with an accuracy of ±(2 to 5%). A reading of 100% humidity means that the air is holding the maximum amount of moisture, or water vapor, and cannot hold anymore. Similar to the DSB18B20, the DHT22 functions on the same voltage range, 3V to 5V, and has a higher max current: 2.5mA which will typically occur when requesting data. The DHT22 also works on a single data pin, similar to the DSB18B20. The downfall of the DHT22 is the sample rate, this being 0.5Hz, meaning you can only request data every 2 seconds. This implies that the data will not be completely live and may even lag slightly behind the other, real-time sensors. Although this sensor can measure humidity as well as temperature while being quite accurate, the sample rate is lower, hence, will not be chosen.

The final temperature sensor, the BME280 shown in figure 40, is more advanced than the previous two. Compared to the previous the BME280 has the features of the DHT22, the temperature sensor and humidity sensor, and also implements a barometric pressure sensor. The BME is less reliable on temperature measurements, having a ±1.0°C of accuracy, with an operating temperature of -40°C to 85°C, similar to the DHT22. The BME has a similar humidity accuracy compared to the DHT22, with a ±3% and operates in between 0 -100% humidity. The barometric pressure component has an accuracy of ±1Pa and operates within the range 300-1100hPa. The BME280 communicates via I2C or SPI with a max rate of 3.4Mhz or 10Mhz, respectively. This is a large leap relative to the DHT22 as the BME will provide the data at a faster rate for a live, accurate description. The BME also functions on the same voltage as the other two options, 3V to 5V. For these reasons: The BME is the more favorable choice of the three. Offering three sensors, temperature, humidity, and barometric, while being accurate. The BME is also able to transfer data much quicker via I2C or SPI.

Figure 40: BME280

There will also be a camera attached directly to the Pi, to be used as a livestream. There are a variety of cameras on the market that will suffice for this project specifically. Therefore, one of the main priorities will be price with respect to functionality and ease of use. Of course, functionality is key. The two types of cameras which will be discussed are USB cameras and Raspberry Pi specific cameras, a webcam and Arducam respectively. Both cameras function for the proper use, utilizing VLC media player to stream live video and will be mentioned again in section 7.5. The difference is the quality of the camera, the price, and the way it is stream is initially accessed. The Arducam, shown in figure 36, is a 5MP camera seen in figure 41 below, and also has multiple lense attachments available to increase the performance.

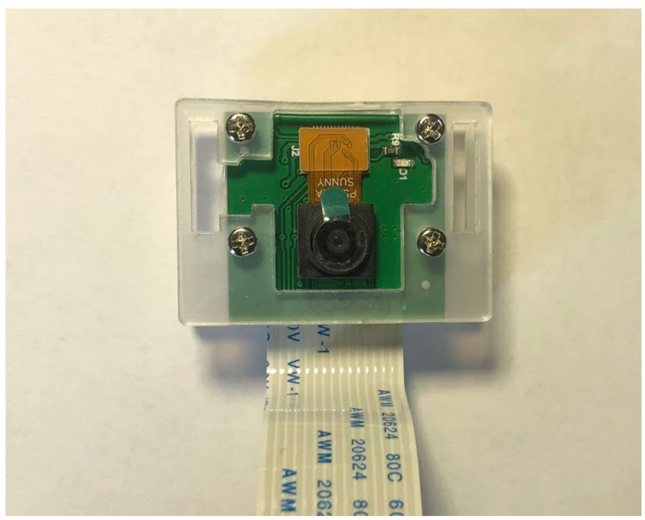

Figure 41: Arducam

It is available at quite a low price: $10 with no lens attachment; each attachment being valued around $20. The Arducam uses a ribbon connector, connecting directly to the Pi board. There are other cameras within this domain offering a variety of features, from IR to Nightvision, and will be used if needed.The USB Camera takes advantage of the four USB ports the Pi offers, instead of the ribbon connection. Unlike the ribbon-connection cameras, the USB camera can be accessed directly via VLC, making streaming video slightly easier. These cameras typically stream at 1080p at 60 frames per second, also making for an efficient live stream. However, where this falls short is on price. For a base USB camera, the cost is quite high, on average $30. This is a significant price jump relative to the Arducam, however, can be used outside of the Pi's domain. Due to this price disparity and the lack of expansions, the Arducam is the more favorable choice, with attachments being used if needed.

7.0 Software Design

To reiterate: the goal of the project is to develop a system which utilizes a combination of premade filters and UV light to cleanse water of pathogens, bacteria, and other potentially harmful chemicals. The overall design will be composed of multiple tanks: uncleansed, cleansing, and cleaned, giving modularity to the project. The system will also contain a User Interface and potentially other software components: this will be the focus of this section.

7.1 Requirements

The requirements for the project were formed through an understanding of the systems design and purpose: as mentioned previously, to cleanse water of pathogens using UV light. The software will act as the interface between the hardware allowing monitoring and backend logic. The majority of the design will be focused on the User Interface, which will be developed to run directly off of the Raspberry Pi.

- User Interface
  - Clean, intuitive UI
  - Display live stream
  - Display measurements
- Software/Hardware
  - Extract data from sensors to be displayed
  - Additional computation for accurate results

7.2 User Interface

Developing the UI to be efficient and easy to use is vital to the operation. Prior to writing the UI, a wireframe design tool to give an overarching goal. Below, in figure 42, is the first prototype for the UI.

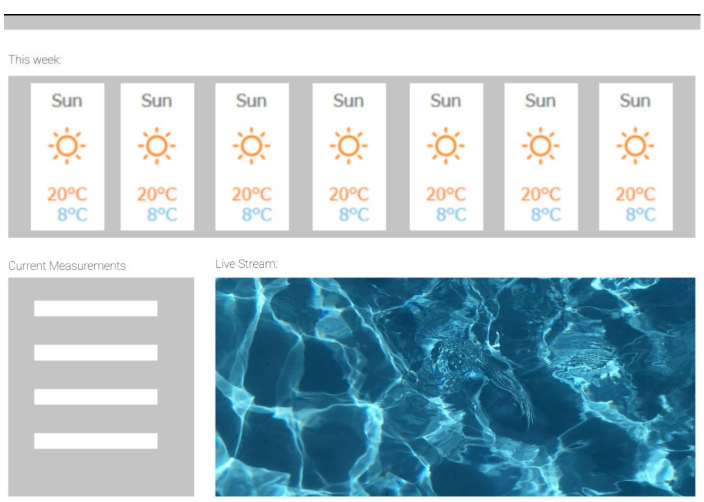

Figure 42: UI Wireframe; Developed in Figma

It should be known that the UI is subject to change as the system evolves. Creating a more efficient, usable design at the discretion of the developers. The UI is the most optimally functional, discussed and up to date, providing the customer with the greatest experience.

7.2.1 UI Design Choices

As seen in the previous section, the UI will be developed as a single page. Firstly, this creates more simplicity on the software side, all while containing the needed information. Secondly, it creates a forced, centralized location for all information regarding water, power level, and any other information deemed necessary.

The top of the page contains the weather forecast for the week. This component does rely on internet accessibility to fetch the data using an API. However, if the system does not have access to the internet, the forecast will be omitted. The Pi will then extract data from the environment using the multiple included sensors to provide an accurate description of the environment. The component was chosen to display temperature as the system will use a combination of sunlight and artificially created UV light.

The Current Measurements section consists of, as stated, current retrieved measurements of the water. The output of the sensors will be displayed here:

- Battery Life
- Water Temperature
- Humidity
- Light Intensity

The above list is only a few of what has been discussed, plenty more measurements may be added. If added, the section of the UI will be modified to account for the additions. Each of these were counted as important or useful.

The battery level will provide information on how long the system can be kept alive, of course. That information can then be used to determine how much water can be cleaned using that amount of power. The water temperature, of course will provide information on the water. This can also be used to further the users knowledge of the current weather. In combination with that, the humidity and light intensity sensors can provide a further look into the environment in which the system is functioning.

Each measurement deemed worthy of being included, all while keeping the page succinct and to the point, leaving the percent error low. The sensors extracting information were chosen and discussed in prior sections: 6.8. Further analysis of technologies to create the UI and display it will be stated in the sections following this; helping create a large scale picture of the hardware-software development and the necessary measurements taken to produce the optimal result.

7.2.2 Current UI Technologies

As this project focuses mainly on system design rather than creating a new system, many previously created technologies will be leveraged. The majority of the used technologies will be focused on the UI development, which is the largest portion of the software design. There are plenty of options for GUI development, from libraries, like TKinter and Qt, to creating a web app, these methods will be discussed here.

The library TKinter, is supported by all platforms: MacOS, Windows, and Linux making it a very versatile library. It is one of the default GUI libraries for Python, being restricted to Python development, and is widely used for the Raspberry Pi. Similar to other GUIs it includes access to the same components: Radio buttons, Sliders, Text Boxes, and more. TKinter does not offer as much styling and therefore the developer is more restrictive than other libraries. An example of this library in use is shown in figure 43.

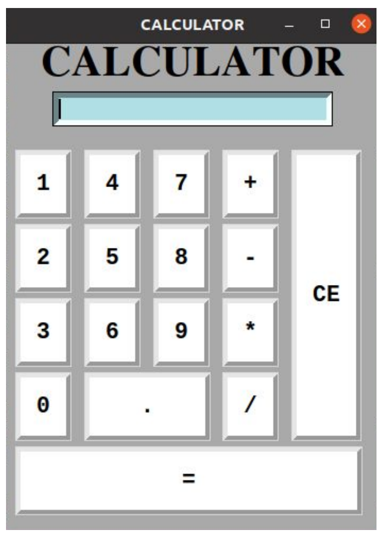

Figure 43: Tkinter Calculator

The Qt library, and is supported by a myriad of platforms and also widely used. Similar to TKinter, it provides access to many components allowing GUI creation to be fluid and reactive. Unlike TKinter, Qt is available to be developed using C, Python, and Java allowing it to be used in more . Qt also offers styling which is similar to CSS/HTML and can be done through the interactive GUI creator, Qt Stdio. The GUI creator offers an import function for Sketch and Photoshop designs. Figure 44 shows an example of the default components used to create a calculator in Qt.

Figure 44: Qt Calculator

Comparing and contrasting the calculator example for both Tkiner, figure 43, and Qt, figure 44, there is a clear difference. First, it can be assumed that the layout can be the same by altering the button properties: width and height. This, therefore, can be ignored.

The other alternative would be to develop the UI as a website. This allows the developer to create the website using HTML, CSS, and Javascript, while maintaining the integrity and functionality of the UI. The developer can also leverage many javascript frameworks: Reactjs and Vueje, to properly style the website. The site would need to be reactive: adapting to different devices, which can also be done using bootstrap and other libraries. This provides a significant amount of freedom with respect to stylistic choices, however, will add complexity in the form of hosting the site. This method is supported and accessed on every platform, from mobile to desktop, as well as every operating system.

Comparing and contrasting the three options, the website variant seems to prevail. It offers a significant amount of opportunity without sacrificing freedom. This contrasts to the other libraries, Qt and TKinter, which limit the amount of customization that one is able to do. Although Qt allows us to customize similar to CSS, it is restricted to a physical LCD/LED display which would need to be attached to the system. As previously mentioned, the website can be served simultaneously among several different devices. Therefore, due to the advantages of the website alternative, relative to Qt and TKinter, the website is the superior option.

7.3 Bluetooth vs WiFi Technologies

There are many data transmission techniques, the two most well known, being bluetooth and Wifi. Both offering their own benefits and drawbacks. The comparison between the two will be a precursor to the following section 7.4 and will aid in the decision making process, giving a brief explanation of the two.

Bluetooth offers a tetherlike connection between two or more devices and used to transfer data. It typically is used in mobile applications however, can be expanded further, to the internet of things. The connection requires a significantly less amount of power relative to WiFi, therefore will be able to operate for a longer period of time. Bluetooth does not need a line-of-sight between devices, unlike infrared, to communicate, and is not significantly affected by object interference. It also offers an asynchronous like feature, with the ability to send and receive data at the same time.

WiFi offers many of the features of Bluetooth, allowing multiple devices to connect and transfer data. Similar to Bluetooth, it is not affected much by object interference. However, it does not offer the ability to send and receive data at the same time, which can come at a disadvantage. WiFi also uses more power than bluetooth, meaning a larger battery is needed to run the same computation for the same amount of time. One of the main advantages, which will be exploited is the ability to create a local network, LAN, and serve applications. This advantages trumps those of bluetooth, and is widely used in IoT; the application of this will be talked about in the next section, 7.4.

7.4 LAN Application and Web-server

As mentioned in section 7.3, we can utilize WiFi to create a LAN. Creating an access point using the Raspberry Pi and multiple libraries: dnsmasq and hostapd. Doing so allows multiple devices to connect to the Pi and view data being extracted. This, of course, can be expanded further to include many other Pi's, sensors, sensors, etc. This, in turn, creates an internal, secure network: an intranet which is completely isolated from the world-wide web. The advantage in doing this, is the Pi can then be accessed from anywhere: meaning, if there is no access to the internet, provided the Pi has power, it will still be able to host the network. This helps accomplish the task presented earlier in the paper; if monitoring will take place in a remote area, data can still be extracted.

Referencing the above paragraph and sections 7.3 and 7.2.2, a web-server can be created and hosted on the Pi. To develop the web-application, the MERN stack will be used. The MERN stack consists of a series of technologies: Mongodb, Express, React, Node for the Database, Site routing, front-end development, and server-side logic respectively. The MERN stack was chosen due to prior experience and the amount of resources available. The front-end and backend will be connected directly, with no need for the database as nothing is needed to be stored. This significantly reduces the complexity of the project, while keeping it both clean and efficient. This leaves the most optimal result, utilizing Node.js, Express.js and React.

The Node and express module handle all server-side logic, as mentioned above. This allows us to run a server hosting our site, updating as needed, directly on the Pi. The Node server will run on an open port, typically 8000, or as decided by the programmer. This can then be accessed similar to the first paragraph mentioned here. If a device is logged on to the access point hosted by the Pi, they will be able to access the hosted website by going to the following location in their web browser:

Pi_IP:Port/

Where the Pi_IP is the IP address of the Raspberry Pi hosting the server, and the port being the designated port as programmed. This makes access to the website relatively easy and can be done on any device. This as mentioned prior, can be the start of an intranet and can incorporate more sensors and can expand to host more sites on other devices, creating a true internet of things.

7.5 Final Software Design

The final design will be a walkthrough of the combination of technologies mentioned in the previous sections. It will be an explanation of the thought process of the build, and each contributing factor, emphasizing anything that may have been previously left out. This will also incorporate the hardware aspect of the UI which was discussed in sections 6.5 and 6.7 and how that plays into the overall design.First, the hardware: the Raspberry Pi which will act as an access point, allowing other devices to connect to it. In doing so, the Pi will be able to create an intranet, as mentioned prior. While doing so, it will also host a server, as depicted in figure 45 where each device connects to the Pi, can talk to each other, and has access to the server, *10.10.10.10:8000*.

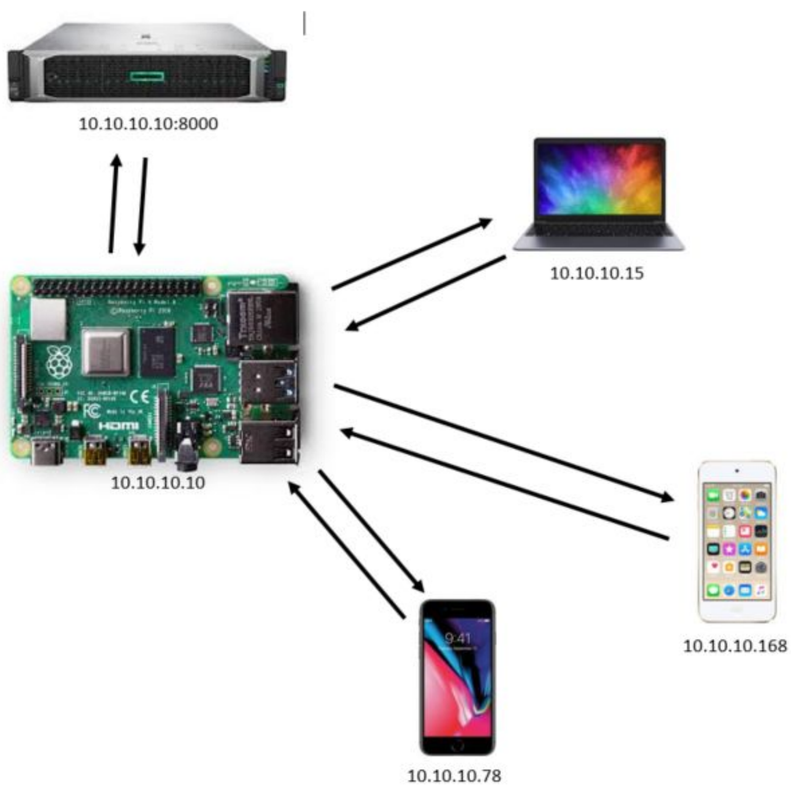

Figure 45: Access Point and Webserver Depiction

The Pi will also be used to gather information, utilizing sensors talked about previously. The BME280 will record Temperature, Humidity, and Barometric Pressure at a constant rate to have accurate and live measurements. To properly capture the value, the adafruit_bme280 library is used and will then be sent to the server using the python requests library (17). The camera will also be attached to the Pi and will be used to live stream data; be it the environment or the water. When used to observe the water, this will act as a visual check in the water cleaning process: checking for large, alien particles. The stream can then be hosted on a port using VLC media player and therefore watched (18).

As stated in section 7.4, using the MERN stack, the frontend will be developed using a combination of Reactjs, HTML, and CSS for the design. The livestream can be embedded within the webpage and can be viewed directly. For the rest of the sensors, the two methods to be used are to use sockets, or have the frontend poll at an arbitrary, decided rate to the sensors. Both offer the same, live rate, with the latter being simpler. The full process, from video and sensor data, to the website is shown in figure 46.

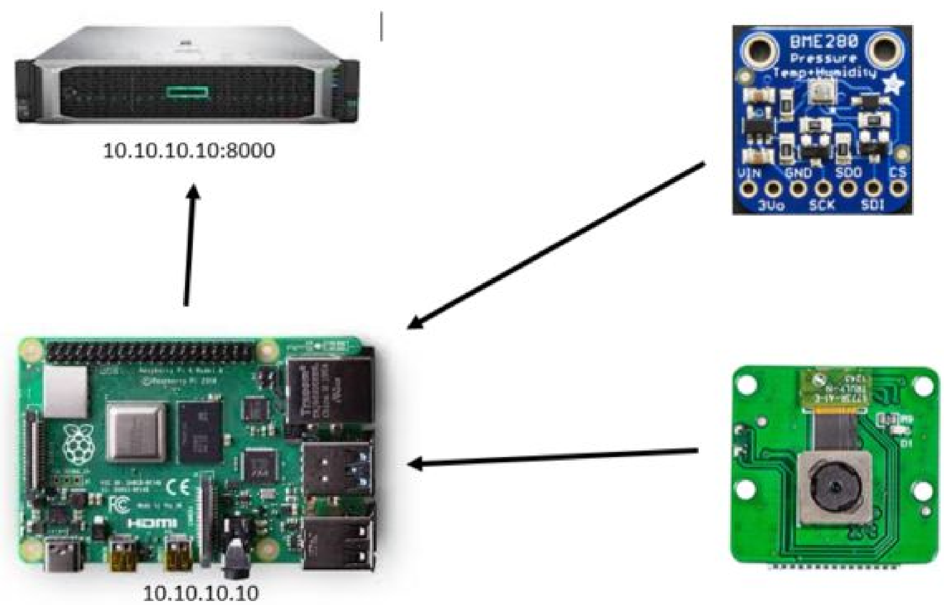

Figure 46: Sensor depiction

The realized design of the above figure 46 is shown below in figure 47. To clarify, the BME280 is connected to the Pi in the following way, shown below and is read as BME280 pin N is connected to Raspberry Pi pin M. Table 23 below shows the pin connections that are going to be made.

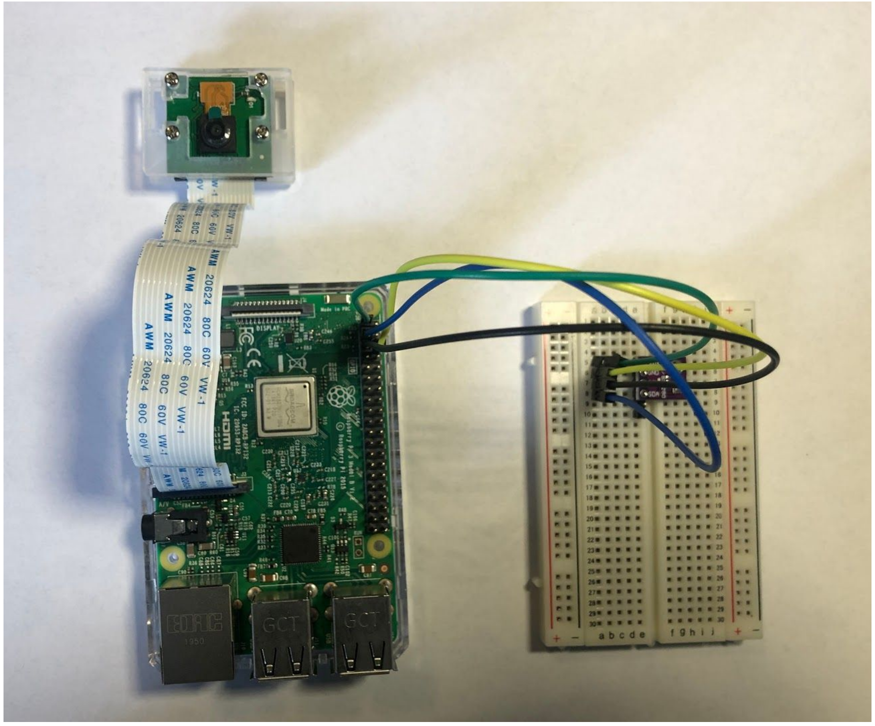

Figure 47: Realized hardware design

Table 23: Pin connections

BME280	Raspberry Pi
V_{in}	Pin 1 (3.3V)
GND	Pin 6 (GND)
SCL	Pin 5 (SCL)
SDA	Pin 3(SDA)

This final configuration of technologies fulfills the requirements of the project goal. With ease, the Pi is able to extract data from the sensors, the BME280 and the Camera module, making it a favorable Microcontroller compared with others which was discussed in section 6.8. The ability to host the Node.js server with easy routing using Express.js makes the process easier. Properly styling the site, using a combination of HTML, CSS and Javascript frameworks make the customization, fluidity, and reactiveness of the UI optimal. As mentioned prior, many devices with different viewports and operating systems, will be able to access the Pi's local network, and therefore access the server and the UI. This makes the system optimal, serving every requirement necessary, allowing for easy expansion.

7.6 Software Milestones

The following table forms a general guideline for the software development process. Each section will contain the initial development, further research, and finally testing. Within the sections time period, there will be individual tests to validate the functionality of that module. Table 24 displays the current status of software milestones below.

Table 24: Software Milestones

Task	Start	Estimated End	Status
Specifications and Requirements	5/11/2020	7/30/20	Finished
Purchase Raspberry Pi	7/1/20	7/30/20	Finished
Set up environment and RPi	7/15/20	7/16/20	Finished
Nodejs and Access Point Setup	7/16/20	7/25/20	Finished
Sensor Measurements	7/20/20	7/25/20	Finished
Develop GUI	7/27/20	9/30/20	Finished
GUI and Sensor Integration	8/10/20	8/14/20	Finished
Final Testing	8/31/20	12/20	Finished

7.7 Results and Conclusions

The final User Interface, with sensor integration is shown in figure 50 below. The view into the tank is shown in figure 48 and figure 49.

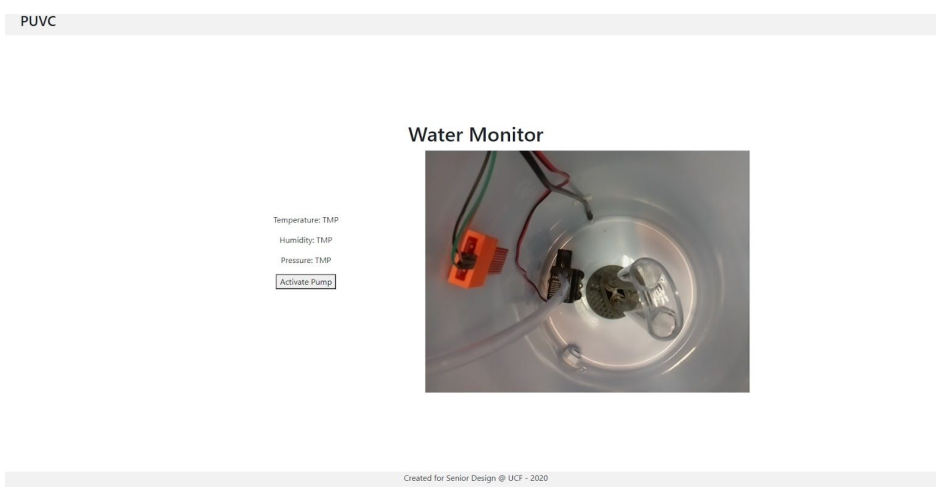

Figure 48: Inside camera view of the tank, lamp off

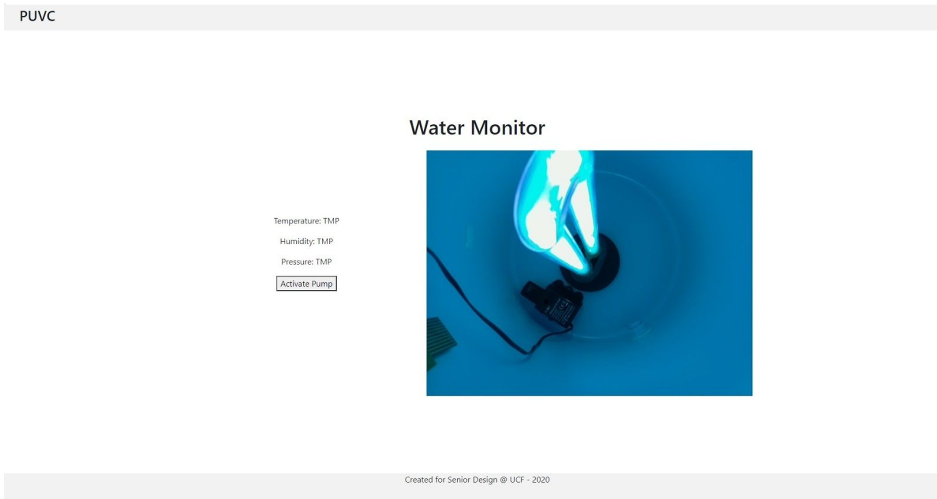

Figure 49: Inside camera view of the tank, lamp on

The camera was positioned on top of the tank to avoid any contact with water while verifying the internals of the system. As seen in figure 49, the lamp is able to turn on, which can be seen using the camera without looking directly into the tank itself. From there, the UI was modified to accommodate more functionality, adding buttons to control both the pumps and the analysis module, which is seen below in figure 50.

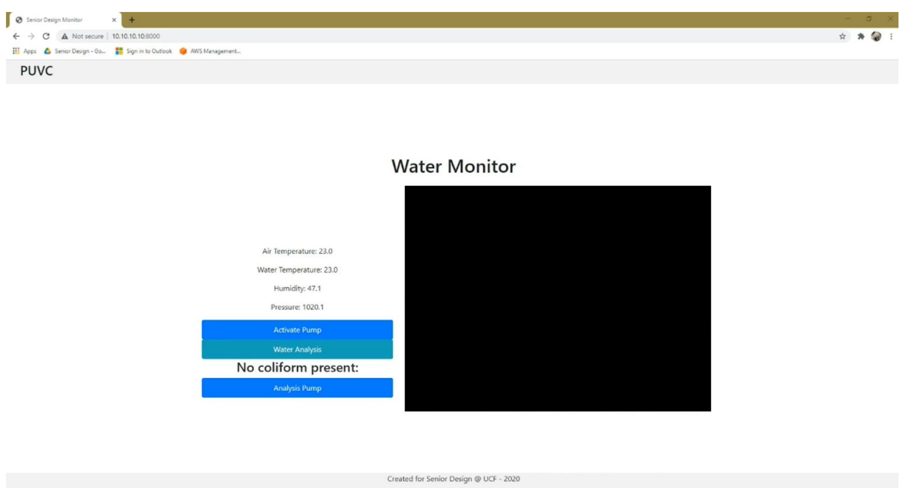

Figure 50: Finalized UI

The WiFi Access Point functionality of the Pi worked as expected, allowing users to connect if they have the proper login credentials. This would then enable them to access the UI and control the system as needed. With the functionality working, there were issues with requests and the latency of response. The main issue stemmed from starting the pump. There was a large delay observed from the button click to the time the pump turns on. This issue was not completely solved. One solution that may prove to be successful would be re-implementing the backend using another Python-based framework: flask, django, or something similar. This would allow the server to directly call the Python script as opposed to using a package to spawn another thread or child-process which is how it was handled in Node.js. The creation of the child-process does not give any priority to it to execute, therefore, potentially starving it for a period of time. Although this occurred with the pump, it did not happen as much with the analysis portion and the serial connection to the PCB. The analysis module was first developed on an arduino and is talked about in the following section and as mentioned prior, was connected and sent data to the Raspberry Pi via the serial connection using the Tx/Rx pins. This allows color data to be extracted and then will populate the *No coliform present:* field in the UI.

The overall system proved to be quite robust in it's conceptual state, but when brought to life seemed to have issues that were unknown prior. Although these problems did arise, the system continued to function as required and needed, therefore not prohibiting or causing the system to falter. The sensors were properly able to extract data and populate the frontend as needed. The frontend was also able to control the system, per the requirements: pumps and analysis, fully integrating and pulling all the pieces together. If more time was added, there would be more investigation into different backend web frameworks, specifically django and flask, to improve the efficiency and time complexity of the system.

8.0 Project Testing

Testing proved to be the most difficult portion of our project planning. As discussed in section 4.2.5 there were many barriers to our ability to successfully test our devices and planned ideas. To ensure that the PUVC is actually a workable idea though we had to perform tests on the vital components. As we gained access slowly back to appropriate labs we were able to then begin outlining or testing procedures so that we had an actionable plan to continue development. We have decided to outline the major testing that we are going to do now that access to the labs is coming back. During senior design two a major focus of the first week will be prototyping the device and testing components. We are also preparing to do these tests at our own homes but are still awaiting some crucial components to arrive. In totality outlined in the following section is the crucial component testing the team had planned as well as the final testing that was done to verify the results of the PUVC.

8.1 LED UV Testing

To ensure that the LED's we received from ILT were actually going to perform as we expect then we had to first test them and compare them to their factory standards. To do this the LED was put through several experimental tests to better catalog the LED's circuit, driving power, output power and several other parameters that are shown in the section below. Testing of any kind proved to be very difficult during the current economic and environmental constraints caused by the pandemic. LED testing was delayed until later in the semester as there was no access to a power meter at first that could register UV rays or any measuring devices that could read low into the UV wavelengths.

8.1.1 Initial Power On Testing

The first test albeit simple was to test that with a simple wire setup the LED's can be operated at their factory given voltages and current. This test will also have to be performed for any LEDs or light emitting device in the PUVC. To test our LED we will connect it to a power circuit regulating the voltage and current to provide enough resistances within the connection circuit to allow proper function. Once the LED is powered on and power can be registered the test is over. Shown below in figure 51 is the LEDs used in the both of the optical arrays.

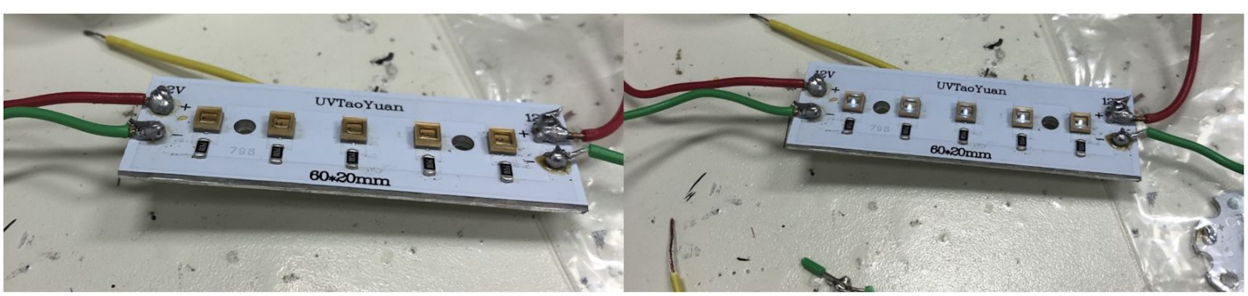

Figure 51 : Shows the initial power on testing of the LEDs used in the design.

The LEDs were then connected to a voltage generation machine feeding it a power of 12V at 250mA. Once the power was turned on as can be seen in the figure above the LEDs began emitting power. The LEDs also emitted a small amount of visible white light. This is later confirmed in the spectral measurement tests of the LEDs shown in section

8.1.2 Output Power Test LEDs

To ensure that the UV LEDs mentioned in the previous section 3 did in fact meet its product specifications a test would have to be performed. The high power LED array that was tested first will provide an initial high power UV dose to the water as it passes between 10 E-275-3 UVC LEDs connected in series. Shown below in figure 52 is the completed design with one LED panel removed to show the orientation of the LEDs along the array. The numbers shown in the photo are to denote the LED in order from top to bottom. The second photo in figure 52 shows a vertical view of the array and red outlined dimensions. The array must be mounted vertically to properly sanitize the water. With the unit in a vertical position the water is able to completely fill the chamber dramatically reducing the turbidity of the water and allowing for greater penetration of the UVC wavelengths as there are no air pockets to disperse the rays. As discussed earlier this final design was chosen for the specific reason of being able to deliver the highest possible UVC dose given the budget of the device.

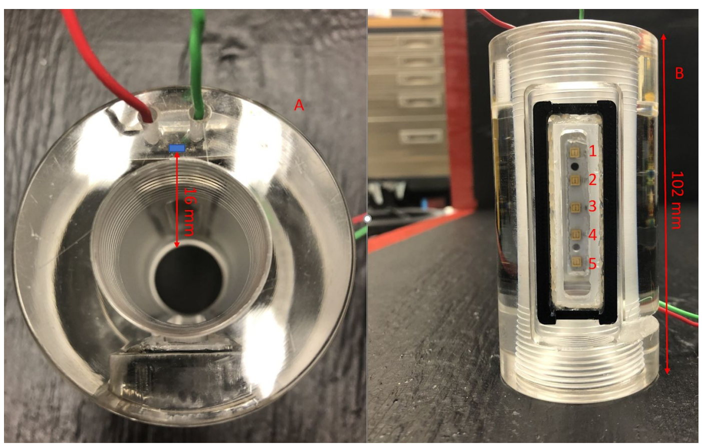

Figure 52: Shown above is a top view of the array apparatus, the blue square denotes the LED and the red measurements denote distance to the array center. (B) Shown is a front view of the array numerically listing the LEDs.

We used this approximate radius of the array to test the power drop off of the LEDs as the distance from the LED approached a max of 16 mm. Shown below in Figure 53 is the relation between distance and power of the LEDs inside the array. We would like the reader to keep in mind that these powers were taken through a quartz window to ensure the listed powers match as closely as possible to processing powers. The total power loss recorded from the quartz windows used on the arrays to protect the LEDs are on average 15.56%. This could be further reduced using anti-reflection coated windows.

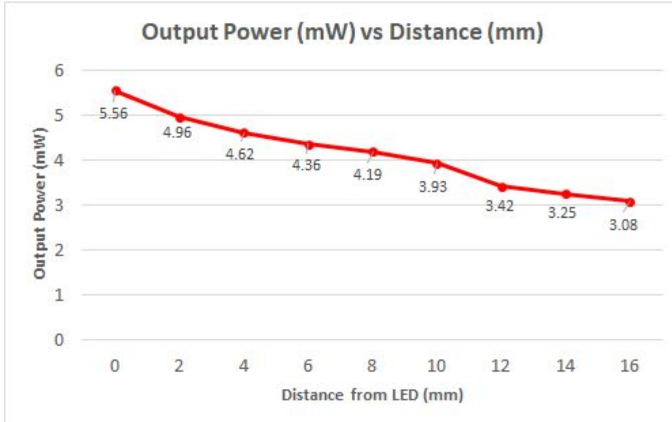

Figure 53: Shown above is the output power vs distance of the LEDs used inside the array.

As can be shown above the power dropoff to the center is near 45%. This although significant still provides a great enough UV dose to perform sanitation. Shown below in figure 54 is the experimentally recorded output powers produced from the LED at various currents. The numerical listing of the LED corresponds to the numeric position of the LED shown in figure 52 above. The LED powers numbered 1-5 are averages of the two LEDs that are parallel in position. The LED total average is shown in green and is the average output of all 10 LEDs.

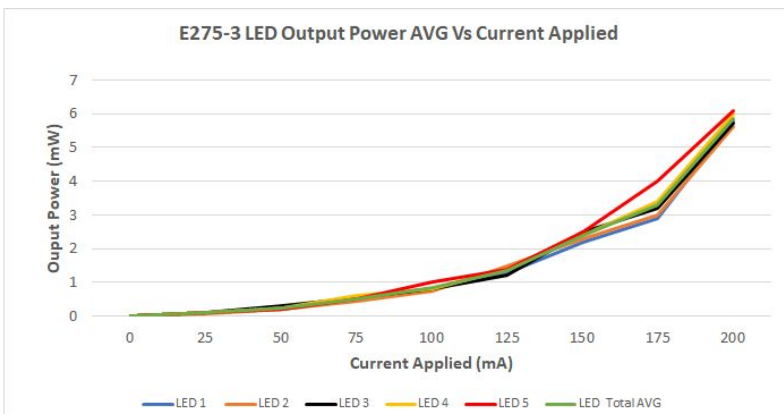

Figure 54: Shown is the E-275 LED output power vs current applied. The voltage was set to 12.42V as the current was modulated.

The team did note that as the LEDs were pushed towards their max power as the position of the LED vertically goes down the max power would seemingly increase. This is due to the experimental method used to take the output power measurements. As consecutive tests of the LEDs were done the panel holding them began to rise in temperature. This increase in temperature corresponded to an increase in the output powers towards the maximum power output rating of the LED at 6.0 mW. Due to the residual heat of the testing done before the last LEDs to be tested, LED 5, was shown to have the highest power. This is purely due to stabilization of power and was proved by the team with further testing.

To calculate the UV dose the team first needed to understand how long the water would be in the array before it moves to the sanitation tank. To get an estimate the team placed small styrofoam balls within the water stream to estimate the time of travel. With the time of travel estimated to be 3-5 seconds in the array a UV dose of 166.8 mJ • m^{-2} can be estimated.

8.1.3 Spectral Measurement Test

To confirm that the LEDs were indeed producing UVC light a spectral measurement was needed. The output spectrum of several different LEDs from the high and low power array are shown below in figure 55. Using a spectrometer the team was able to verify that the center wavelength of the diodes was indeed close to the 275 nm required for effective cleaning. While it is not exactly at 275 nm this should not impact the germicidal efficacy as most coliforms are susceptible to wavelengths in the range of 245-350 nm. In figure 55 below one can also notice a distribution of intensity within the visible wavelength regime, these wavelengths will have no impact on the germicidal effect and will not interfere with the UVC efficacy therefore the team did not create an optical system to eliminate it.

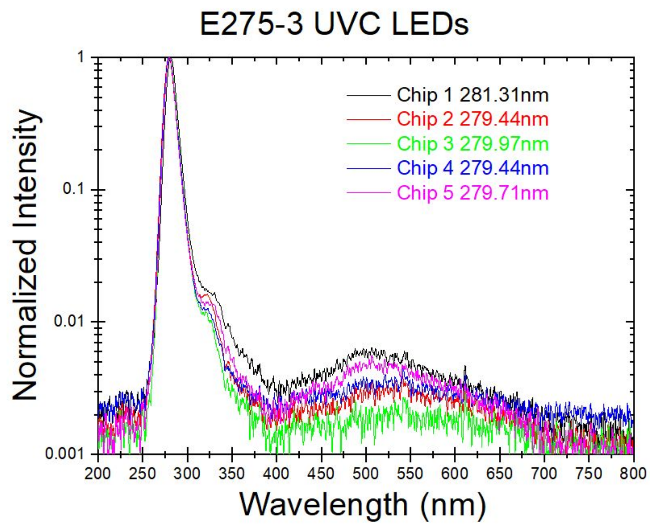

Figure 55: Shown is the output spectrum of 5 of the UVC LEDs used in the array.

The following figure 56 displays the difference in the respective intensity peaks of the previous 5 tested LEDs.

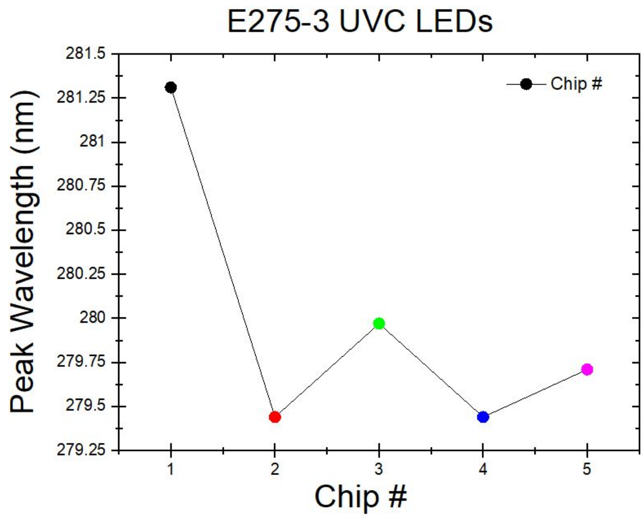

Figure 56: Shown is the center wavelength corresponding to peak intensity produced from the LEDs.

As can be seen above all 5 LEDs are very close in peak wavelength value. The LEDs were tested sequentially from 1 to 5, therefore due to a decreased temperature of the board we believe the LED #1 peak wavelength was pushed to a greater value. This is further displayed as the difference in the following 4 LEDs tested at a stabilized temperature were much closer in value.

8.1.4 Collimation test

To ensure that the proposed lens design is in fact able to collimate the LED as we would like the collimation lens setup must be tested. To do this the three lenses will be aligned on an optical table and adjusted to the lengths predetermined in section 5. A custom 3D printed mount for the LEDs was designed and built for the tank as well as custom mounting for all three lenses. The lenses were aligned concentrically with the central LED in the mount. The optical setup used for the experimental measurements is shown below in figure 57 as well as the LED array employed. The final optical array will maintain the distances shown in figure 57.

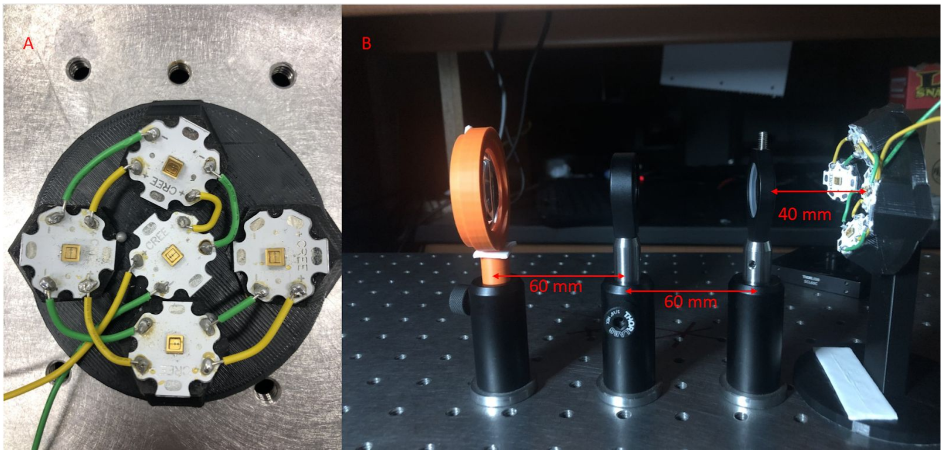

Figure 57: Shown above is (A) the LED array to hold and aim the 5 LEDs used in the ambient array as well as (B) the optical setup and distances used to produce the output shown in figure 58

To demonstrate how the LED light was redistributed a simple test was done to prove the collimation of the LEDs. Shown below in figure 58 is a demonstration of the redistribution of the LED output pattern.

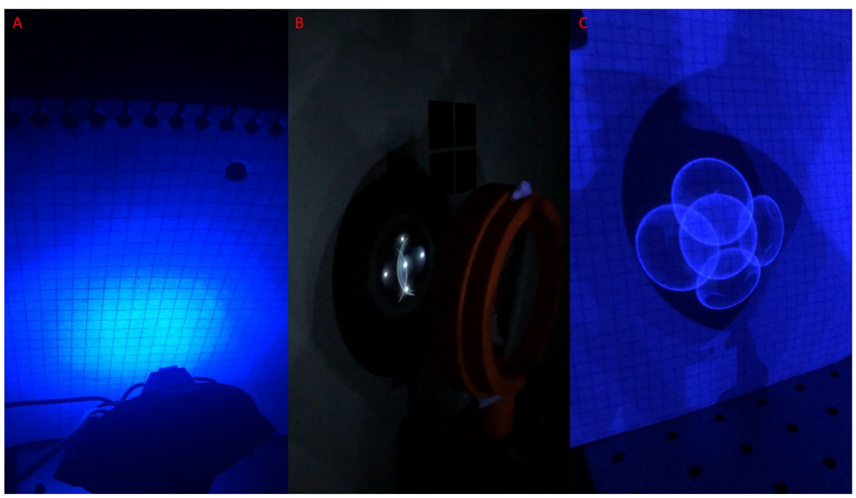

Figure 58: Shown above is the collimation testing done for the low power array.(A) The output profile without any collimation at 5 cm from the array. (B) The output profile after the LEDs have been collimated and 5 cm from the final lens.(C) The output profile from the collimated LEDs at 25 cm.

With all these parameters set the UVC ambient array was able to produce a dose near 30 mJ $\bullet\, m^{-2}$. This is significantly less than the high power array as the loss from the lenses and quartz window added together is near 80%. This is fine for the application as the array is simply used as an ambient cleaner and should not be capable of performing initial sanitation, only preventing new growth.

8.2 Output Power Test UVC Lamp

The high power UV-C producing lamp will serve as a backup when there is a greater power needed to clean the water of coliform. Once it has been determined by the verification system that the water is indeed still infected with coliform the device will then allow for the user to turn on the lamp and irradiate the water. The mercury lamp that was selected for the device is the Ster-L-Ray G18T5L-U (G18). The G18 has a total power output of 18.4 W. This power is not all in the UVC regime. The lamp when activated to produce UVC radiation will through the heating of the mercury output a wavelength range of 200 - 700 nm.We were unable to get a max power measurement of the device as doing so would oversaturate the power meters available to the team. To overcome this the team planned out with Atlantic Ultraviolet, the provider of the lamp, to ensure that testing could be done before the lamp was sent to us to guarantee the appropriate power requirements were met. Through their testing they were able to verify an overall power of 18.2 W from the device, 5.4 $W \bullet m^{-2}$ specifically in the UVC wavelength regime.

The team did expect this as the remaining power being emitted is in visible wavelength regime. The team determined taking a measurement of these powers would show no relation to the efficacy of the device and therefore it has been omitted from this paper. With this power and with a duration time of 10s the UV dose produce is 54 $J \bullet m^{-2}$. This power is substantially greater than needed and can in fact be reduced by more than half and provide the same efficacy. The operation of the lamp and photos of the lamp in the chamber can be found in section 7.

8.3 Water Height Sensor Testing

For the PUVC to properly function the amount of water coming into the device must be controlled and stopped if it rises too high. To do this as mentioned earlier we will employ a water sensitive device to monitor where the water is at within the tank. To ensure this will in fact work the team will take the device, insert it into water and then test whether the device we have selected indeed connects when exposed to water. Upon completion of this the next step will be to test electronically how the system will allow this newly connected circuit to power off the pumps. To do this the pumps will be connected via an electronic circuit to the water sensitive device and operated. Once the device is plunged into the water the fans should turn off. These tests while simple will be vital to the PUVC to ensure that overflow and damage to the unit will not occur.

8.4 Testing of battery chargers

The testing procedure of Lead-Acid Batteries used in Photovoltaic systems outlined in IEEE Std 1361-2014 was used as a guideline for battery testing. An adjustable power supply that can provide constant current charging for charging the battery and a resistive load for discharging the battery will be needed for this test procedure. The battery will first be fully charged using the power supply before the test. Then, the initial battery capacity of the battery will be measured at the test rate for one cycle. Next, the batteries will be cycled to mimic the daily cycles of a PV system as conditions change depending on the available solar radiation. At least 20 cycles will be tested. Finally the battery capacity will once again be measured to determine the performance of the battery charging system. If the final battery capacity is equal to or greater than 80% of the initial battery capacity then the charging system works as intended. A final capacity range of 80% to 90% indicates that the solar charge system can be improved by modification of various parameters, the charge rate for example. The solar panel output power will also be measured throughout the test process to ensure that the panels are working as intended to provide enough power to power the system and recharge the battery at a reasonable rate. The same procedure for solar charging will be adapted for charging the battery via wall outlet. The purchased battery charger will be connected to a wall outlet and after measuring the output voltage of the charger which should be about 14 V the battery will be charged and discharged over several cycles in a similar manner to that of the solar charging testing.

8.5 Testing of DC/DC converter and DC/AC converters

The 12 V and 5 V DC/DC converters will be assembled on a breadboard using the specified components from their respective schematics. The testing of the DC/DC is necessary to ensure that the voltage is regulated so that no voltage spikes will damage the electrical components that make up the PUVC. The input to the DC/DC converters will be connected to a power supply and a multimeter connected to the output for output voltage measurements. The voltage of the power supply will be incrementally varied from some voltage below the design input voltage up to a voltage that is significantly higher than the design input voltage. If the voltage measured by the multimeter is consistently 5 V for the 5 V DC/DC converter and consistently 12 V for the 12 V DC/DC converter then the voltage components of the converters are working as intended. Next the maximum output current will be tested. A variable resistor will then be connected across the output nodes. As the resistance is varied decreasingly, the current through the variable resistor should increase up to the maximum current output specified in the design parameters. Once the current reaches this maximum current, there should be no more increase in the current beyond the maximum current. Only after modifying the design if necessary and ensuring that the voltage is correctly converted and regulated will the componnets be soldered onto the circuit boards. We expect that the DC/AC inverter will work out of the box but it will be tested nonetheless before being connected to the power system. A power supply will be set to 12 V and connected to the input and the expected output should be in the range of 110 V to 120 V at a frequency of 50 to 60 Hz.

8.6 RGB and CdS Testing

Testing of the RGB LED and CdS photocell is required in order to determine the best configuration of the water quality analysis module to ensure consistent and accurate results. There are a few factors to consider for the testing of the color sensing method. Reflection and transmission of light into the water sample will affect the optical power viewed by the CdS. The ratios of reflected light and transmitted light can be manipulated via the placement of the optical components in the PUVC analysis module. The choice of how to place these components is ultimately governed by the principals of the Fresnel equations. Different angles can be chosen to reflect more light at different polarizations. Another factor that can affect the accuracy of the detection method is the optical path length of light traveling from the LED to the CdS photocell. The other two factors to consider when testing are the effects of turbidity and dispersion. The turbidity of the sample will increase the absorption of light in some configurations and thereby reduce the optical power viewed by the CdS photocell. This will primarily affect the response of the photocell when viewing the transmitted spectrum rather than the reflected spectrum. Dispersion in the water sample will also primarily affect the transmitted spectrum as the light spreads into its component wavelengths in water. There are more factors to control for when analyzing the transmitted spectrum compared to the reflected spectrum which makes the method less desirable. There is however one key tradeoff that increases the viability of viewing the transmitted spectrum, and that is simply the optical power levels. Because water is highly transparent most of the optical power emitted by the LED will be transmitted, leaving very little light to be analyzed via the reflection spectrum.

8.6.1 LED Power Testing

Test one will determine the optical power output of the LED. The LED will be aimed directly into a power meter. The voltage supplied to all 3 pins will be maximized for the chosen LED and the total optical power will be recorded. Next the voltage for the green and blue pin will be reduced to 0 while the voltage to the red pin will be maximized. The total optical power emitted from the red LED will be recorded. This procedure will be repeated for both the blue and green pin, the voltage applied to the blue pin will be maximized while the red and green pin are reduced to 0 and the voltage applied to the green pin will be maximized while the red and blue pin are reduced to 0. This test will determine the total optical power emitted by the RGB LED as well the optical power emitted by each of the LEDs individually. The setup for this test is shown below in figure 59.

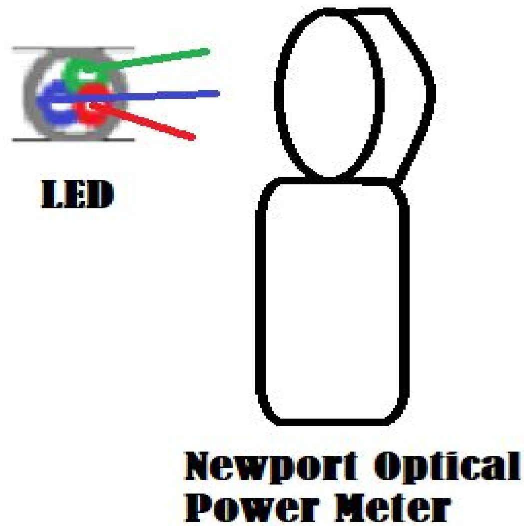

Figure 59: Visual Representation of power testing configuration.

Next the voltage supplied to each pin will be varied at regular intervals from the minimum operating voltage to the LED's maximum operating voltage according to the datasheet provided with the LED. At each voltage level total optical power will be measured and plotted to give a relationship between applied voltage and optical power output. This relationship will be used in test two to verify the existence of a linear response of the photocell's resistance to the output power of the LED. Test one provides information about the output power of the LED at different voltages that are ultimately used in test two to construct a plot that shows this linear response.

8.6.2 Resistivity Testing

Test two will be conducted to measure the response of the CdS photocell to each LED. The resistance of the photocell will be measured with an ohm meter while no light hits the cell. The LED will then be aimed directly at the CdS photocell. The voltage to each pin will be maximized and the resistance of the photocell will be measured again. Similarly to test one, the photocell then be exposed to each individual LED, red green and blue individually while the others are off and the resistance of the photocell will be measured for each. The resistance will then be plotted against wavelength to give a rough estimate of the response of the photocell. The setup for this test is shown in figure 60 below.

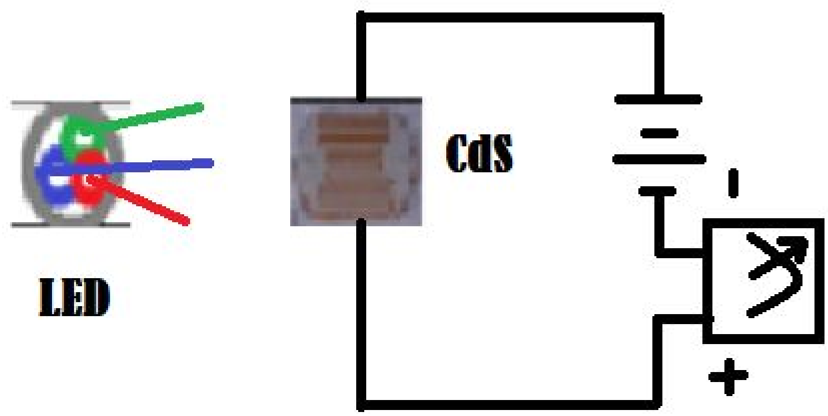

Figure 60: Visual Representation of resistivity testing configuration and circuit diagram

In order to ensure the detector is operating with a linear response over the visible spectrum the voltage supplied to the LED will be varied to change luminosity of the LED. The resistance of the photocell will be measured at each voltage interval and the results will be plotted on a graph that displays optical power vs resistance. The value of optical power will be based on the measurement taken in test 1 that relates voltage to output power.

8.6.3 Reflected Light Color Sensing Testing

Testing will consist of two water samples one positive and one negative for coliforms. As discussed each sample will have a distinct color associated with a positive and negative result. Test three will determine the viability of the preferred optical setup. The CdS photocell and RGB LED will be placed side by side as shown below in figure 61.

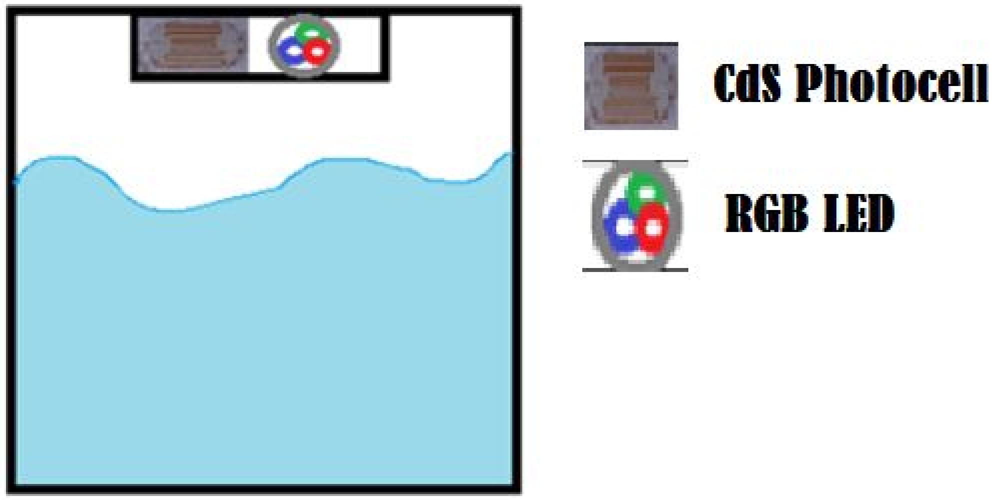

Figure 61: The reflected light color sensing configuration

In this configuration the LED light will be emitted into the sample at normal incidence and the reflection off the samples surface will be viewed by the CdS. At normal incidence approximately 98% of the optical power will be transmitted and 2% reflected, based on calculations from the Fresnel equations. Each sample will be analyzed one by one and the results will be compared to see if the two are clearly differentiable by the CdS.

8.6.4 Path Length Testing

Test four seeks to optimize optical path length of light traveling from the RGB to the CdS photocell. The discussion on Beer-Lambert's Law showed that the absorption of light in a water sample is proportional to the optical path length. For this test a positive and negative sample for coliforms will be used. For each sample three optical path lengths will be tested to compare the performance of the system's ability to differentiate between a positive and negative result at each length. The three setups that will be tested will include 5.5cm of air and 5mm of water sample, 5 cm of air and 1 cm of water sample and 1cm of air and 5cm of water sample. This totals to an optical path length of 6.165cm, 6.333cm and 7.665cm for each configuration respectively. The LED will be positioned above the water sample and the CdS below the water sample. A visual representation of the setup for test four is shown below in figure 62.

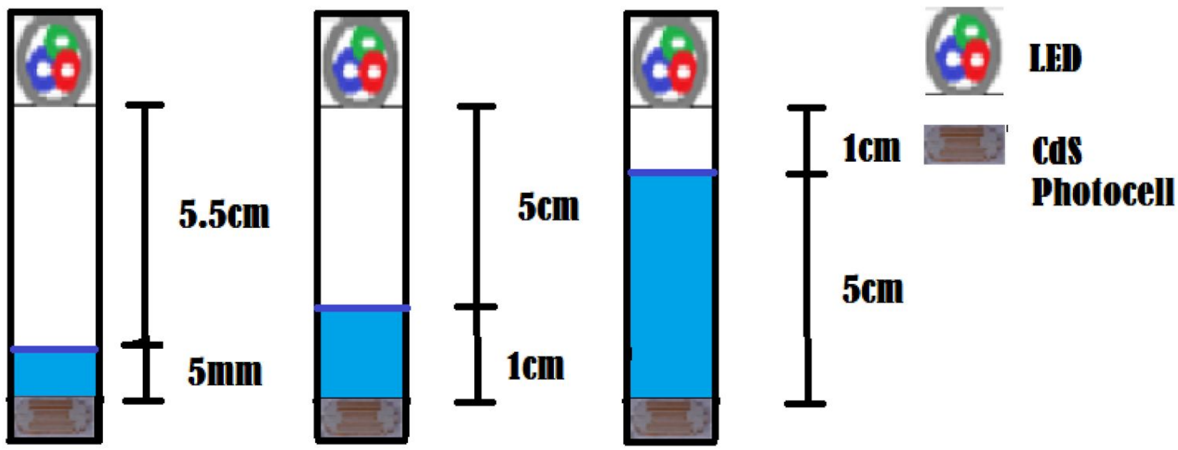

Figure 62: The pathlength testing configurations for each trial.

The samples will be analyzed to see if changes in the optical path length have a noticeable effect on the ability for the system to differentiate between a positive and negative result for coliforms. The results of these tests will help determine path length that will be used in test five and ultimately the final system.

8.6.5 Transmitted Light Color Sensing

The configuration of the RGB LED and CdS will be changed from the setup in test three to resemble figure 63 shown below

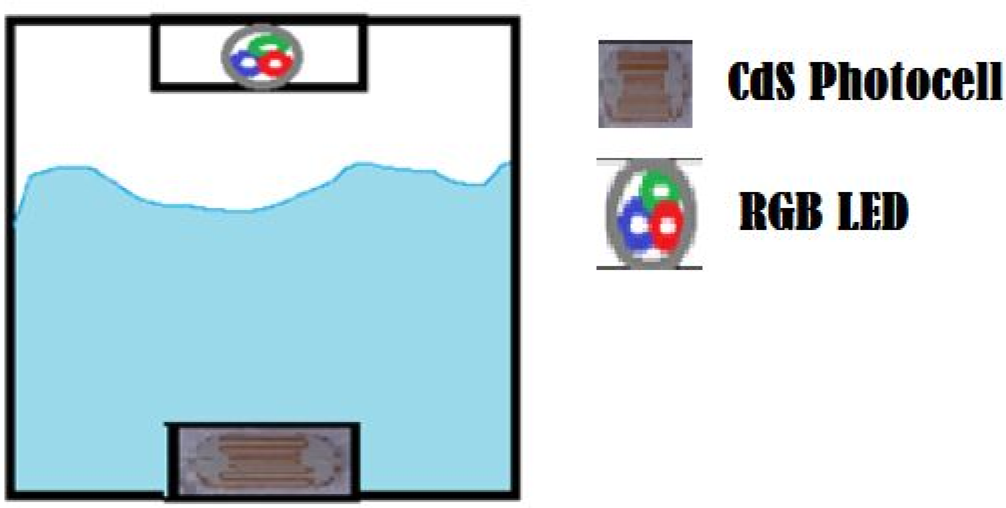

Figure 63: The transmitted light color sensing configuration

Testing in this configuration will follow the same procedure as test three. The main difference is the CdS is viewing light from the transmission spectrum instead of the reflected spectrum. This configuration would result in a higher optical power for the CdS to detect, though it is marginally affected by the turbidity of the sample and the dispersion of light as it travels through the water. The two samples, one positive and one negative for coliforms will be tested and the results will be compared to see if they are differentiable in this configuration.

8.6.6 Angle of Incidence Effect on Color Sensing Testing

If neither configuration in test three or test four are producing good results then a third option can be explored. The third option would be to orientate the LED so that the angle of incidence onto the water's surface is larger than 0 degrees. The advantage of angling the LED would be a substantial increase in reflected power for some polarizations. At 60 degrees for example the reflected power for S polarized increased to 11.5%. This does however have a trade off, only .5% of P polarized light would be reflected. The light from the LED is randomly polarized and can be considered 50% s polarized and 50% p polarized. So it's still a net gain in reflected power regardless of the trade off. The configuration for this test would resemble figure 64 below

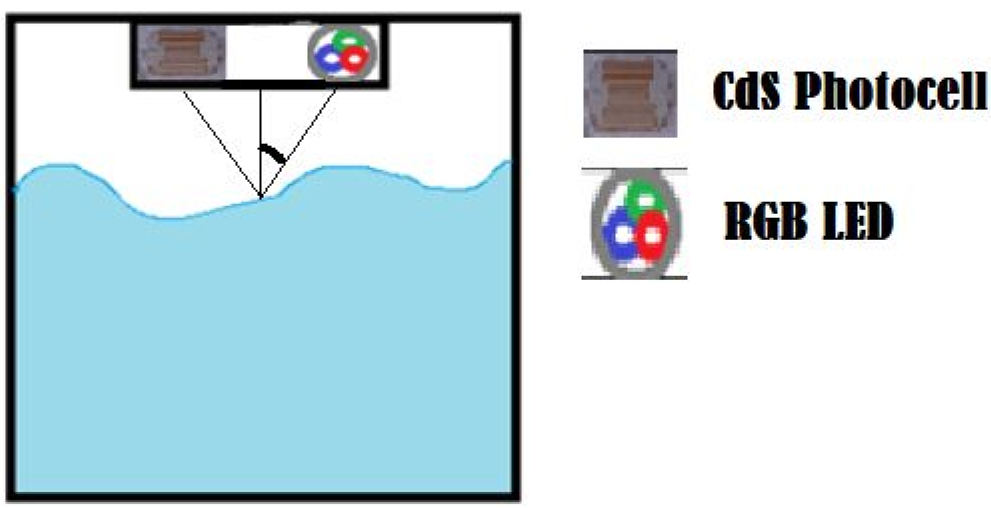

Figure 64: The angled reflected light color sensing configuration

At a 60 degrees angle of incidence the procedure of test 3 and 4 will be repeated, the two samples would be compared to see if they are differentiable by the detector, The angle of incidence would be adjusted in increments of 5 degrees down back to 0 degrees and each increment would be compared. The results from these tests can then be compared to find which angle produced the most differentiable results. Differentiability is measured by how large the measured spectrums vary from the positive and negative sample.

8.6.7 Color Sensor Testing Results

The color sensor testing determined that capturing the reflected light as opposed to transmitted light was the best way to determine the color. A longer optical path length also produced more accurate results. Shorter path lengths resulted in high intensity light on the photocell which saturaturated the sensor. Given more time I would do an additional test beyond 7.66cm to about 12.5cm optical path length. The module itself was poorly designed in hindsight and would need to be revisited to commercialize the PUVC. The color of the module would need to be transparent and the height dimension would need to be increased to store a larger water sample and increase the optical path length of the reflected light being captured by the photocell.

The sensor was able to differentiate between positive and negative samples, however it was not accurately determining their true color. The blue-green color associated with a positive sample for coliforms was interpreted as a dark green color and the off yellow color associated with a negative sample was interpreted as pink color shown in figure 65 below.

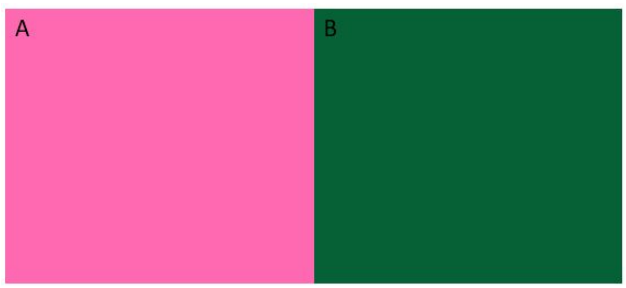

Figure 65: (A) Sample negative for coliform bacteria (B) Sample positive for coliform bacteria

We believe these results occurred from a combination of poor module design, strict optical path length requirements and slow response speeds associated with the photocell.

8.7 Software Testing

As mentioned in section 7, the software component contains multiple, modular components which will need to be tested. Due to the relative complexity, the testing only needs to be at par with the module being tested; keeping the test at a minimum, yet comprehensive state, showing the most optimal data to be examined. The tests, expected results, and results that will be discussed here are the following:

- Access Point Testing
- Sensor Testing
- User Interface Testing

Utilizing the libraries dnsmasq and hostapd, the Pi, as discussed prior in section 7.4, can be used as an access point. This proves to be a key feature in this design, allowing users to access the server which is hosted on the Pi. We can test the feature and decide the success by the requirements given below:

- Pi AP shows up on devices using WiFi
- Devices are able to properly connect to the Pi
- Devices can ping the Pi directly, ensuring a connection
- Devices can ping each other, ensuring routing

Each ensures that the AP functions as needed, providing connection to each other and to the Pi itself. This designates that the server run on the Pi can properly serve pages to the connected devices.

Second, the sensors will need to be tested to verify that they are properly extracting the correct information from the environment: from both the Camera and the BME280. Testing the Camera is quite straightforward, properly plugging it in to the Pi, then using the raspivid command in the terminal to verify that it is functional. Testing the BME280 is slightly harder. Before verifying that proper values are being calculated and output, it needs to be properly connected. To verify this, the Pi should output the voltage needed, 3.3V, and be connected via I2C. This is then enabled within the Pi's interface. The verify that the BME is connected via I2C, running the command, *i2cdetect -y 1*, will notify if there is a device connected on the address 0x77. Once the sensor is connected, the proper sensor readings must be configured and tested. The verification process will be done via comparison with another device, ensuring that both measure the same value. This will be done for temperature and humidity. Barometric pressure will be slightly different, and will be tested as needed.

Finally, there will be tests done on the User Interface to verify the integrity of it. The UI, as mentioned prior in Section 7, will need to be reactive: alters display to properly accommodate different viewports. The most important view being mobile, then laptop and desktop. The site will also need to properly update, as discussed, to display the proper sensor readings at a reasonable rate. To verify reactiveness, the site will be tested on multiple platforms: desktop and mobile. Both cover the different sizes of viewports and will allow for further optimization. To verify that the website is updating properly, a python script which will be used to extract and send data to the web server, will also log the values in the console. This can then be verified directly and visually.

The methods of software testing used here create a comprehensive data set, verifying the integrity of the platform and technologies used. Testing every component on an individual basis first, then expanding to the overall system. This demonstrates that each component works properly, slowly adding components to achieve the final result, which functions as expected. As said, this set of tests can be further expanded upon, however, keeping it relatively simple generates the optimal data needed to verify that the system works as needed.

9.0 Administrative content

This section will detail all the administrative content necessary for our senior design project. This section will explain the milestones we set out with in the beginning and our final milestones. Most of the major changes have already been mentioned in previous sections therefore, additional explanation behind each change will not be given. We would also like the readers to again keep in mind all these dates were set during the COVID epidemic that is still unfolding. Due to great uncertainty and inability for us to predict what will happen next much of the planning must be flexible. We were able to accomplish many of our major planned goals despite these roadblocks, although due to the testing constraints mentioned in section 4 we have been greatly delayed in the testing of key optical components. In conclusion the following sections will definitely outline our original thought process to how the PUVC would progress and then show how these timelines have changed at the end of senior design 1.

9.1 Milestone discussion

In this section are our milestone sheets that we created during the different phases of design and design plan that we went through. As we got more research done and ordered more parts we had to change a variety of timelines and expect completion dates. These changes reflect the problems and solutions outlined in all previous sections. To not include an overcomberson amount of milestone charts we chose the first and final milestone chart to highlight the overall changes made to the system and prototype pollans. The team is although still conscious that these dates will also most likely change as more decisions are made by the government and UCF in regards to the COVID epidemic. Table 25 and 26 below show the milestones for each portion of the project.

Table 25: Initial Milestone Sheet Number 1

Number	Task	Start	End	Status	Responsible
Senior Design I					
1	Ideas and Group Formation	5/11/2020	5/15/2020	Completed	Group
2	Project Selection & Role Assignments	5/11/2020	5/15/2020	Completed	Group
	Project Report				
3	Initial Documentation - Divide and Conquer	5/18/2020	5/29/2020	Completed	Group
4	Divide and Conquer V2	6/1/2020	6/5/2020	In Progress	Group
5	60-page Report	6/5/2020	7/3/2020	In Progress	Group
6	100-page Report	7/3/2020	7/17/2020	In Progress	Group
7	Final Documentation	7/17/2020	7/28/2020	In Progress	Group
	Research and Design				
8	UV Cleaning Research	5/15/2020	5/29/2020	In Progress	Joe
9	Spectroscopy Research	5/15/2020	5/29/2020	Completed	Raymond
10	Design Specifications	5/25/2020	7/1/2020	In Progress	Group
11	Design of Cleaning System	5/25/2020	6/15/2020	In Progress	Group
12	Design of User Interface	5/25/2020	6/15/2020	In Progress	Nidiyan
13	Design of Electronics	5/25/2020	6/15/2020	In Progress	Damian
Senior Design II					
14	Building of Prototype	8/24/2020	12/1/2020	Not Started	Group
15	Testing and Redesign	TBA	TBA	Not Started	Group
16	Final Prototype	TBA	TBA	Not Started	Group
17	Peer Presentation	TBA	TBA	Not Started	Group
18	Final Documentation	TBA	TBA	Not Started	Group
19	Final Presentation	TBA	TBA	Not Started	Group

Table 26: Milestone Sheet Number 2

Number	Task	Start	End	Status	Responsible
Senior Design I					
1	Ideas and Group Formation	5/11/2020	5/15/2020	Completed	Group
2	Project Selection & Role Assignments	5/11/2020	5/15/2020	Completed	Group
	Project Report				
3	Initial Documentation - Divide and Conquer	5/18/2020	5/29/2020	Completed	Group
4	Divide and Conquer V2	6/1/2020	6/5/2020	Completed	Group
5	60-page Report	6/5/2020	7/3/2020	Completed	Group
6	100-page Report	7/3/2020	7/17/2020	Completed	Group
7	Final Documentation	7/17/2020	7/28/2020	Completed	Group
	Research and Design				
8	UV Cleaning Research	5/15/2020	5/29/2020	Completed	Joe
9	Spectroscopy Research	5/15/2020	5/29/2020	Completed	Raymond
10	Design Specifications	5/25/2020	7/1/2020	Completed	Group
11	Design of Cleaning System	5/25/2020	6/15/2020	Completed	Group
12	Design of User Interface	5/25/2020	6/15/2020	Completed	Nidiyan
13	Design of Electronics	5/25/2020	6/15/2020	Completed	Damian
Senior Design II					
14	Building of Prototype	7/20/2020	12/1/2020	Completed	Group
15	Testing and Redesign	7/20/2020	9/10/2020	Completed	Group
16	Final Prototype	9/11/2020	12/4/2020	Completed	Group
17	Peer Presentation	8/24/2020	12/4/2020	Completed	Group
18	Final Documentation	8/24/2020	12/4/2020	Completed	Group
19	Final Presentation	8/24/2020	12/4/2020	Completed	Group

9.2 Budget and finance discussion

To be able to effectively complete our project build we had to create a defined budget. Due to the COVID pandemic as well our cost and build management must be properly planned so that the project can move forward effectively. To do this all team members spent time doing cost analysis for their respective parts and performed research into which electronic, mechanical, and optical parts would most cost effectively complete our build. Table 24 below shows the overall budget for crucial components of the PUVC.

Table 24: Budget of PUVC

Item	Vendor	Price Per Unit	Amount	Total Price
UVC LEDs	ILT	$14	14	$196.00
UV Lenses	Edmund	$160	3	$480.00
UVC Lamp	SLRU	$116	1	$116.00
Raspberry Pi 3b	Adafruit	$35.00	1	$35.00
Water Tank	Gatorade	$25	1	$25.00
Water Pumps	Amazon	$11.00	3	$33.00
Solar Panel	Amazon	$41.00	1	$41.00
Solar Charge Controller	Amazon	$15.00	1	$15.00
12 V SLA Battery	Amazon	$31.00	1	$31.00
PCBs	JLCPCB	$54.00	1	$55.00
PCB components	LCSC	$35.00	1	$35.00
AC Battery Charger	Jun-Electron	$13.00	1	$10.00
Inverter	Amazon	$40.00	1	$40.00
Quartz Windows	EKSMA	$40	3	$120.00
Pre-Processing Filter	Amazon	$35	1	$35.00
Arduino UNO	Arduino	$23.00	1	$23.00
RGB LED	King Bright	$11.88	1	$11.88
CDS Photocell	Adafruit	$9.94	1	$9.94
Coliform Test Kit	CWS	$16.90	1	$16.90
Arducam 5	Jun-Electron	$10.00	1	$10.00
Water Level Sensor	Adafruit	$14.00	1	$14.00
BME280	KOOBOOK	$5.00	1	$5.00
DS18B20	IZOKEE	$5.00	1	$5.00
3D printer material	Makerbot	$69.00	1	$69.00
Total				$1,431.72

10.0 Epilogue and Conclusion

The reason that we chose the PUVC as our senior design project is that we see it as a product that has wide ranging potential not only in application but also in its ability to impact the health of a large number of people. Also with the recent epidemic we believed the project would have a great impact in our understanding of pathogens and pathogen reduction. Being that as of now the project is very open ended we are able to think of a variety of additional elements to add to our design that could simplify the process or allow for additional applications. These applications include water fountain sanitation, sporting water sanitation, hospital water sanitation and even a means for the everyday outdoorsman to extend his ability to stay offgrid. As is well known we also encountered several school firsts during our document's lifetime. The entire school was shut down as well as a seemingly endless continuous morphing of many institutions surrounding us and that we depended on. This added stress made organizing the initial idea far more strenuous then it would have been if the team was simply able to meet face to face. All of this though did not discourage us to any great extent and we are optimistic for senior design two as we know it will provide us with invaluable experience in design, implementation and communication.

Our document and project was completed through a variety of steps due to the unique and difficult to navigate quarantine due to COVID-19. The main way we were able to accomplish the document and project despite our circumstances was in three main phases. The first phase was that we researched all relevant technologies to better understand what we could use and how to use it. Once we understood our options we then selected the specific parts we wanted to use and cataloged all necessary information about them. Once we had the parts we then moved to the most difficult to implement phase, our testing phase. Due to a lack of any ability to enter UCF campus we were forced to create pseudo labs at our homes and attempt to perform accurate testing. This proved extremely difficult as long lead times, inadequate equipment and no outside physical assistance left us separated as a team. Although this project is simple in its implementation we encountered a great amount of difficulty due to our quarantine constraints and the variety of features that must work cohesively for our project to function. We hope this document illustrates the work we have put into this project to work around these unprecedented circumstances and how the team was able to work around this to complete the testing in the end. The team had to push hard at all times to complete the project given the circumstances. Planning ahead for senior design two turned out to be an essential part of our document given the recent COVID restrictions. Due to the fact that we again did not have access to our essential senior design lab, equipment, and teachers in person we saw it as crucial to attempt to plan for this inevitable scenario given the current state of the country.

In totality the PUVC challenged the team in ways we had never been challenged before and we believe we produced the best possible prototype we could deliver. We not only researched extensively but also heavily tested the device to ensure its ability to sanitize. We had to change the design at multiple points either due to change of material or due to extended lead and excessive cost. Despite these challenges the team was able to complete a prototype of the PUVC that is capable of sanitizing water through UV at a speed and volume not seen on the market.

Due to several advantages the PUVC has over its competitors we believe the system if funded would have great success. The team only hopes that this success will lead to more people around the world having clean water and the freedom to live a healthy life.

Appendix

Citations and Research Articles

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