

UCF Senior Design 2

Optical Chlorine Concentration Analyzer

Final Project Document
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Chapter 1 - Executive Summary

Our Optical Chlorine Concentration Analyzer aims to display chlorine concentrations in water accurately within a relatively compact system that combines optics, hardware, and software. The project draws inspiration from current water treatment technologies, aiming to develop an easy solution suitable for daily use by both professionals and individuals alike. As many water treatment plants increasingly rely on UV technology for water purification, accurately monitoring chlorine levels becomes essential for effective disinfection. Our system is created with this use in mind, making the operation as simple as possible with great results. Designed with accessibility in mind, our solution features a mobile application with a user-friendly interface, making it accessible and easy to operate for users with varying levels of expertise. Additionally, our system is no more than \$500, making it affordable for most companies.

Chapter 2 - Project Description

2.1 Project Background and Motivation

Senior design is the university's way of taking our learned theories and experiences both in classroom lectures and laboratory experiments and making us apply them in a way that can solve an existing problem. This project encompasses what engineers really do in the world: they observe complex problems and work with available resources as well as personal abilities to develop an innovative solution. Given that our group is composed of one Photonics Science Engineer (PSE) and two Computer Engineers (CpEs), we wanted an idea that would involve gathering a great amount of data from an optical design and then process that information through well-developed software. Our project seeks to create a responsive system that can detect free chlorine content in a water source. The PSE will be responsible for designing a system that detects the chlorine content in a water sample while the CpEs will be responsible for designing the system which takes the optical signal and converts it to an electrical signal which can be processed and interpreted by software. Additionally, the CpEs will also develop a mobile application that can be used via Android phone to view information about the water sample's chlorine concentration easily, as well as display where the reading was taken.

2.2 – Current Commercial Technologies and Inspirations

2.2.1 – Previous Senior Design Project: Fish Tank Assistant

The Fish Tank Assistant is a previous senior design project which aimed to assist fish tank owners in the upkeep and care of the condition of their enclosure. By using an optical system that uses the Beer-Lambert law in tandem with a thermal camera, the project was able to detect and notify its owner of shifts in the condition of the water. Their group consisted of two PSEs and two CpEs, which made their idea of particular interest since their documentation answered the major concern of how we'd take an optical signal and convert it to an electrical signal without an electrical engineer (EE). Their primary focus was specifically on detecting and notifying owners of algae blooms, which can occur in any water that fits the following description: warm, slow-moving, and filled with nutrients. According to them, the algae can produce a fast-acting poison known as a Cyanotoxin which can kill any marine life within. Even if this toxin isn't produced in the water, an excess of algae in the water can quickly deplete the oxygen within the tank, resulting in water incapable of supporting the pet fish within. This is the primary motivation behind their desired system.

Their final system was capable of detecting the algae with an interface that the owner could use to easily note how much algae was present and advise when to clean the fish tank. Additionally, they reached a stretch goal of being able to siphon water from a source into a test tube. While they weren't able to reach all their goals, they more than proved that their system was feasible and gave our group the idea to look into contaminants in water and seek to go one step further. That further step is to decontaminate, which is what led us to our next inspiration.

2.2.2 – Current Senior Design 2 Project: Smarter-Portable Water Bacterial Detector

One of the senior design projects currently in development is a UV light disinfectant. This group aims to detect microorganisms in water and use a specific UV wavelength to kill them. Their PSEs are currently in the process of building the optical system that will detect and kill microorganisms in the water, while their CpE works on developing software to assist the owner of the product and the EE builds the optical signal to electrical signal interface. The working principle for their project is using the UV wavelength of 254 nanometers, which is a particularly effective wavelength to destroy bacteria, parasites, and any other harmful microorganisms in a water source, to disinfect drinking water.

When initially discussing how to build off the algae project, we were made aware of and reached out to this group for information on their idea and current goals and objectives. Due to the high effectiveness of 254 nanometer UV light, most

microorganisms that can be dangerous are all handled by this singular wavelength at a power of 1 watt and above. For this reason, we realized that we could not use UV light to kill biological organisms as that would have near identical goals and objectives to this current project. Thus, we researched articles online about water treatment and found that at a similar power of 1 watt and above, one could break down chlorine in water using UV light and use a filter to reduce the concentration of chlorine. For good measure, we reached out to a company which does water treatment using UV light and had them affirm our idea, which is our next section and fits into the category of current commercial technologies.

2.2.3 – Rodem: Smart Sanitary Processes

Our group looked into various companies that use UV light in their water treatment process and eventually decided to get in contact with Rodem. This company uses a variety of sanitization methods to fulfill given parameters a customer requests of them. For example, if the water needs to be used for pharmaceutical purposes, they will incorporate a complex, multi-stage water treatment process due to the necessary purity of the water. Due to their processes having multiple stages, they have experimented with and successfully incorporated various systems which utilize UV light to purify water. Some of their systems use the aforementioned 254 nanometer UV light to disinfect and deal with bacteria, but a few other systems have also used a different wavelength to reduce the concentration of chlorine in their target water sample. After a few phone calls and consistent pestering, we were able to get in contact with someone who gave us an excellent starting point and overview of how water treatment plants go about purifying water.

Brian Gorchowski is the contact that we eventually reached after asking various employees around Rodem about the properties of chlorine in water. He is a regional sales manager based in Kentucky who works closely with Rodem. The company he actually works with is known as Nuvonicuv and their primary selling point is their UV-based solutions for disinfecting a variety of surfaces such as air, physical surfaces, and most importantly, water. He described to us how the UV at a certain wavelength range breaks down free chlorine in water into its ions which then reform into byproducts that are very easily removable via a reverse osmosis filter [68]. He also gave us a better understanding of why using UV is beneficial in comparison to using other methods such as activated carbon filters. The specific drawback to activated carbon filters lies in that the damp surface of activated carbon fosters the growth of bacteria, which can easily reduce the purity of the water. While there is a variation of activated carbon which takes this into account and prevents the growth of bacteria, Gorchowski described it as very costly and usually not worth the purchase in their applications. This overview gave us a far better understanding of water treatment, which gave us a clearer vision of the function we wished our project to fulfill. After the phone call, he sent an email with valuable information to help us deduce what wavelength to use.

2.4 – Goals and Objectives

The Optical Chlorine Concentration Analyzer should at minimum do what its namesake entails: Detect free chlorine in a water sample with a high level of accuracy. This will serve as our overall goal, with the previous senior design projects from section 2.2 serving as inspirations for our advanced and stretch goals.

2.4.1 – Basic Goals

Basic goals encompass the bare minimum of what the optical chlorine concentration analyzer should be capable of.

1. Design an optical system that can detect and accurately report the amount of chlorine content in water in ppm.
2. Have at least 88% accuracy when detecting chlorine in a water sample.
3. Develop a mobile application for android phones that displays concentration of chlorine in the system, as well as send information to the user through email.

2.4.2 – Advanced Goals

The advanced goals of our system should go beyond what the basic goals entail and should still be achievable. Advanced goals generally encompass the fine tuning of the system and the mild expansion of certain systems within the product, giving us a path to improving the product's performance once the bare minimum is achieved.

4. Achieve an accuracy rating of 95% or greater.
5. Create a database for every unique user and system.

2.4.3 – Stretch Goals

The stretch goals of our system are typically a path that can be taken but pose a significant challenge to the development of the product. Be it due to having to heavily expand and complicate a subsystem or due to constraints related to budget or product size, we expect to meet these goals only partially after the advanced goals are achieved.

6. Expand the system to be able to test and display information about more than one water source at a time and expand the mobile application accordingly to give updates without impeding the understanding of the user.

7. Expand the mobile application to be functional on both iOS and Android devices.

2.4.4 – Objectives

The first set of objectives are geared towards ensuring our basic goals are reached and satisfied. They are what each student is doing on a weekly basis as we progress towards completing our basic goals. The first six objectives are in chronological order, with the application development being something worked on in the background as we reach our objectives.

1. Research spectroscopy and laser attenuation methods for detecting chlorine content in water and select one.
2. Using knowledge of objectives 1, decide on how much water will be tested, as well as the sample holder for our system.
3. Use the results of the previous objectives to design the layout of the optical system for detecting chlorine, as well as take note of the full power requirements of the optics system.
4. Use the results of objective 3 to integrate the electrical components of the system into the design and ensure all components interact without conflict.
5. Order parts and create the prototype of the design we've developed, then tweak the system to fulfill our basic goals (Accurate detection of free chlorine in water sample).
6. Design the housing of the project with consideration to size of components in Solidworks and 3D print all sections, then assemble the housing.
7. Develop a mobile application in the form of an APK (file usable by android mobile devices) that can accurately display our detected chlorine content from the prototype.

Once the first seven objectives are fulfilled, our basic goals are achieved and we can move on towards advanced goals and stretch goals, which have the following objectives:

- For our first advanced goal, achieve 95% accuracy, the system must be perfectly aligned and the PCBs which hold our photodiodes must be perfectly created to reduce noise to a negligible level. Perfect alignment ensures less fluctuation in read values and better PCBs results in less noise which can obscure our signal.
- For our second advanced goal, create a database that holds a unique ID for every user and system. We would use a nonrelational database such as MongoDB and everytime a new customer creates their log in information we would assign them a unique ID through the backend server, this way we would have a system in place to avoid duplicate entries.
- For our first stretch goal, expansion of the system for multiple tested water sources, more interactions between optical, electrical, and software

components can easily make readings more difficult to keep track of. Thus, our mobile application will need to become far more robust to remain capable of displaying information from multiple sources. Additionally, the expansion of the optical system itself demands a larger project housing, which can exhaust our valuable resource of time since 3D printing is a long process.

2.5 – Current Required Specifications

Table 1. Requirements Specifications

Requirements	Parameter	Description	Specification
Chlorine in Water Detection Range	Detection Sensitivity	The Optical Chlorine Concentration Analyzer should be able to detect chlorine concentrations.	0.5ppm - 10ppm
Accuracy	Reliability	The Optical Chlorine Concentration Analyzer should give an accurate reading of the current concentration present in the water.	> 88%
Response Time	Speed	The detector should be able to report results on the app within a minute of the initial data collection.	< 1 minute
Environmental Conditions	Temperature Resistance	There should be a defined operating temperature and pH for the detector. We also want to identify any environmental conditions that could affect the detector.	Room Temperature (~293 K) pH between 6.5 to 7.5
Photodetector Sensitivity	Input Sensitivity	Have our photodetector be sensitive enough to record a discernible difference in power to determine chlorine concentration	Dependent on laser power
Laser Diode Specifications	Wavelength Required	The laser diodes wavelength should be that it matches with the absorption spectrum of the DPD so that we achieve a readable signal in our Photodiode	520 nm

Power Consumption	Power Required	Define an acceptable power consumption for the sensor if it is deployed at a remote location.	5W-10W
Cost Constraints	Budget	We want to make sure the project does not exceed \$1,000.	< \$1,000
Dimensions	Size	It should be less than 1x1x1(m) to ensure the system is portable and easy to set up in a lab setting.	< 1x1x1(M)
Maintainability	Durability	The Optical Chlorine Concentration Analyzer should be able to run for an extended period without maintenance or supervision.	> 1 year

2.6 – House of Quality

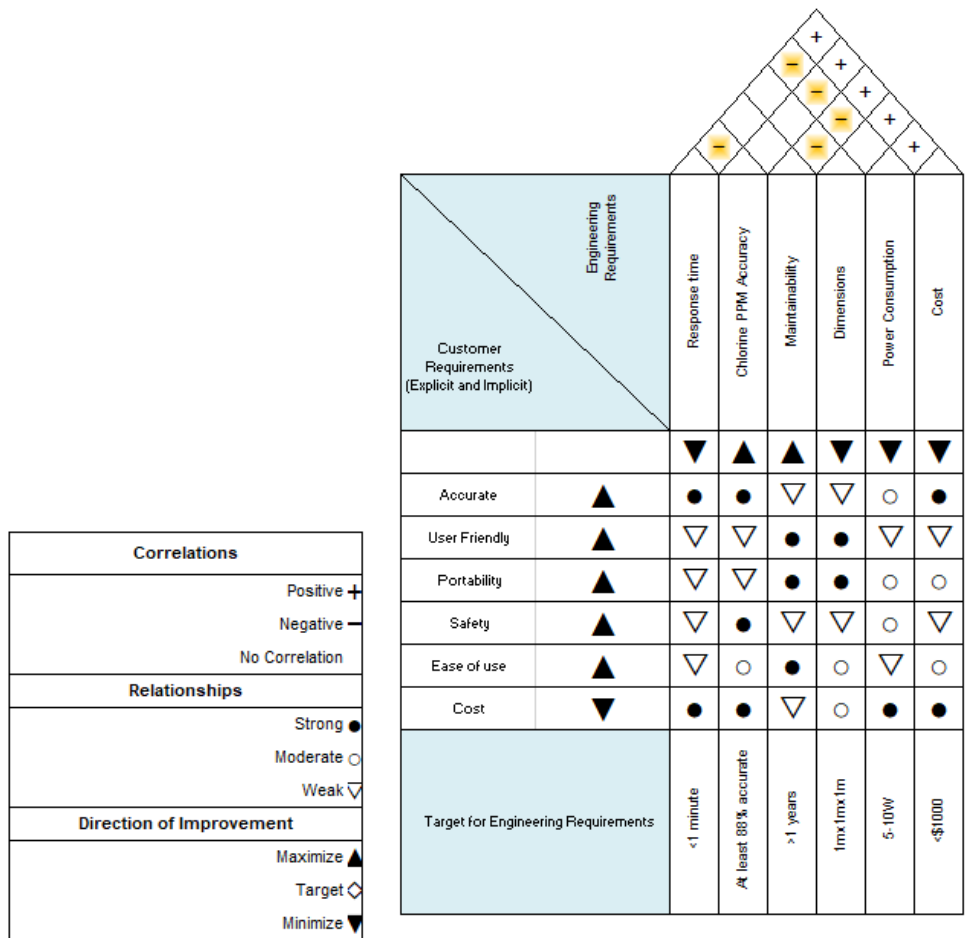


Figure 1. House of quality

2.7 - Hardware Block Diagram

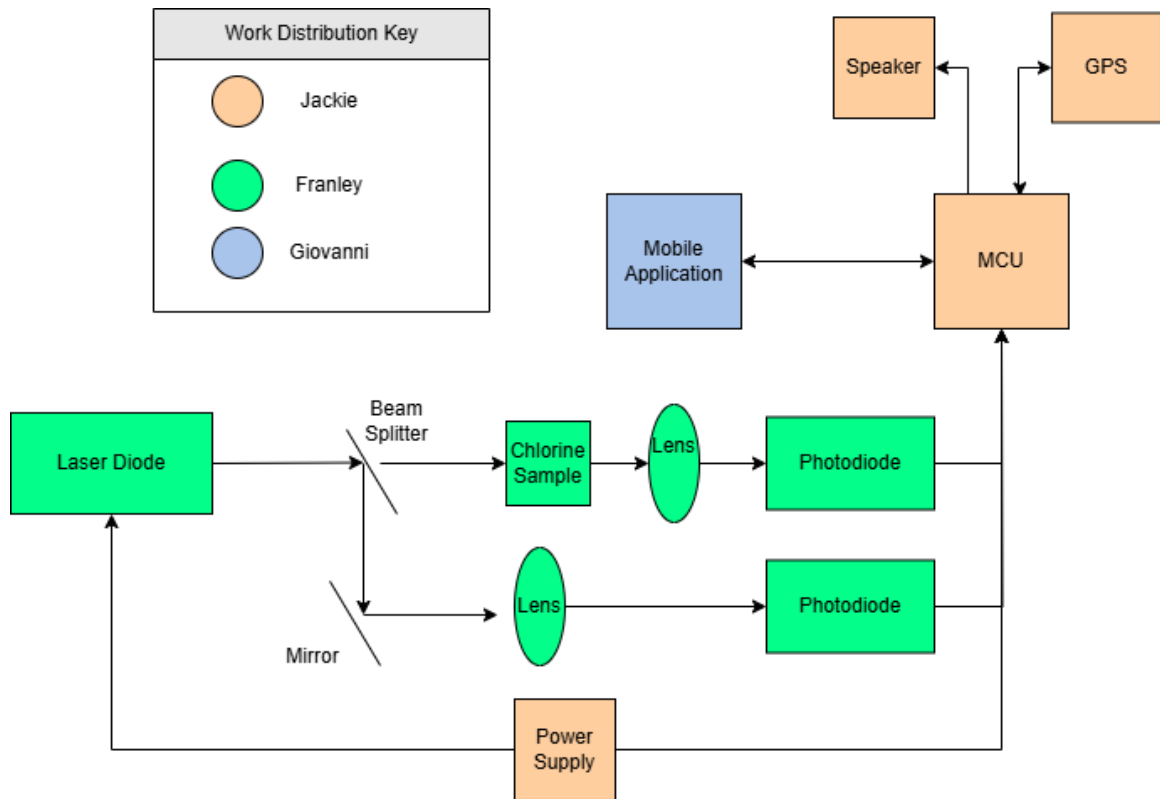


Figure 2. Hardware Diagram

Our hardware block diagram comprises several key components working together seamlessly. At its core, a laser diode emits a beam that is split by a beam splitter, leading to two distinct paths. The first path directs the beam towards a photodetector, facilitating the measurement of the beam's power. Meanwhile, the second path guides the beam through a chlorine sample for concentration detection. When the beam encounters the chlorine sample, the laser's power is attenuated, which can then be compared with the first path's laser power. Based on the optical loss, we can calculate an approximate chlorine concentration in parts-per-million. All these components interface with a microcontroller responsible for both laser diode control and concentration readings. Additionally, our system integrates a mobile application, providing users with convenient control and monitoring capabilities. This comprehensive setup ensures precise measurement and ease-of-use, enhancing the reliability of the system.

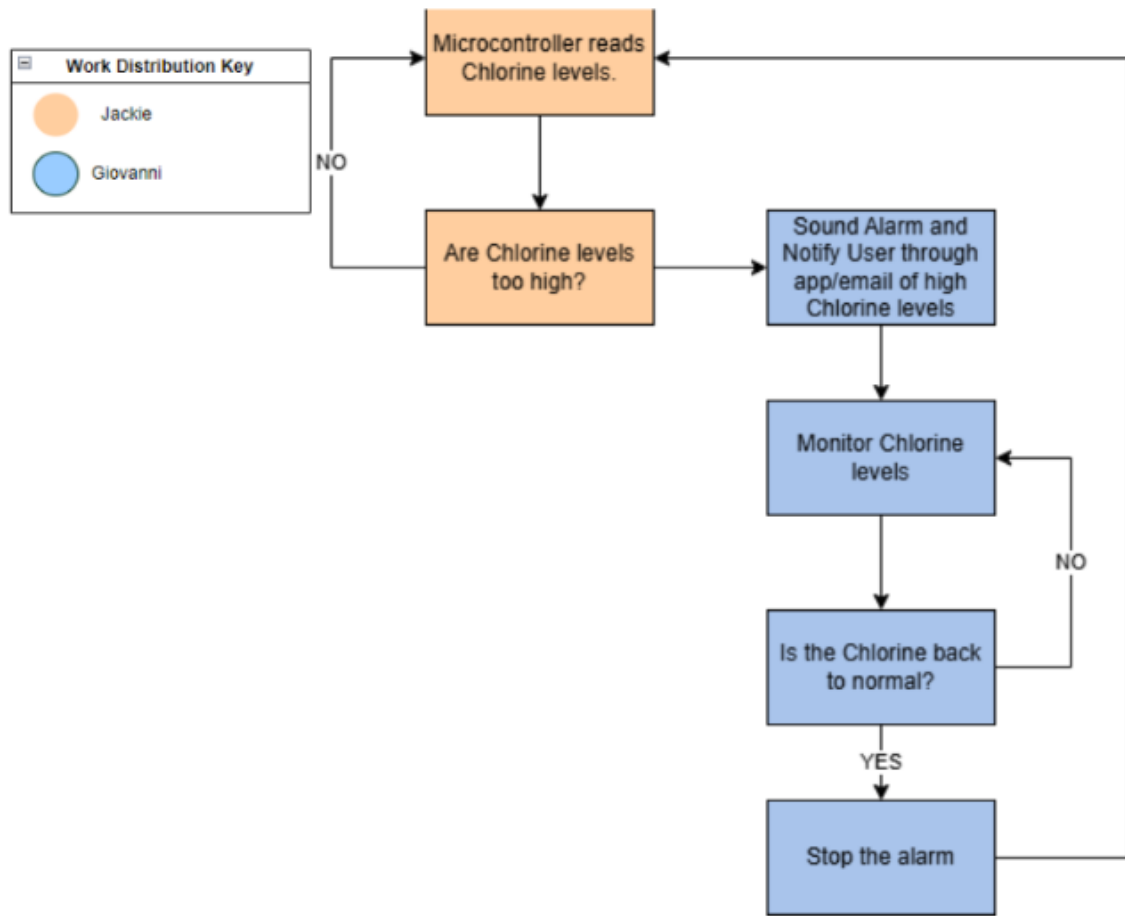


Figure 3. Software Diagram

2.8 - Optical Layout

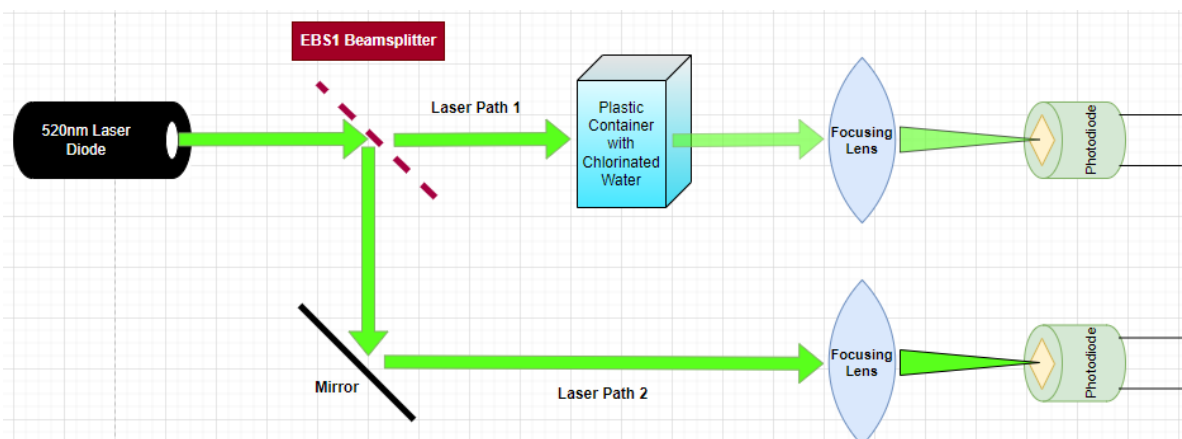


Fig. 4. Current Optical Layout. Laser path 1 has its power attenuated after passing through the chlorinated water. Laser path 2 reaches the photodiode unimpeded.

Chapter 3 – Research and Background Information

3.1 Chemistry

Chlorine, a highly reactive chemical element, plays a crucial role in water purification due to its powerful disinfectant properties. In the context of water treatment, two main forms of chlorine are of significant importance: total chlorine and free chlorine. Delving into their chemistry provides insight into their roles and significance in water purification processes.

Total Chlorine: Total chlorine encompasses all forms of chlorine present in a water sample, including free chlorine, combined chlorine, and chloramines. Free chlorine refers to the unbound, active form of chlorine that is available for disinfection purposes, while combined chlorine includes chloramines formed through the reaction of chlorine with ammonia or organic nitrogen compounds. The measurement of total chlorine provides an overall assessment of the chlorine content in the water, offering valuable information for water treatment strategies.

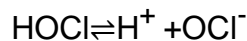
Free Chlorine: Free chlorine, as mentioned earlier, represents the active, unreacted chlorine present in water. In water treatment, free chlorine is particularly effective in disinfecting water by oxidizing and destroying pathogens such as bacteria, viruses, and protozoa. Chemically, free chlorine exists primarily as hypochlorous acid (HOCl) and hypochlorite ions (OCl⁻), depending on factors such as pH and temperature. The equilibrium between these two species is pH-dependent, with hypochlorous acid being more prevalent at lower pH values, where it exhibits greater disinfectant efficacy due to its membrane-penetrating properties.

Chlorine's Role in Water Purification: The process of water purification involves the addition of chlorine to water in carefully controlled concentrations to achieve disinfection while minimizing undesirable byproducts. Chlorine acts as an oxidizing agent, disrupting the cellular structures of microorganisms and rendering them inactive. This disinfection process involves several chemical reactions, including the oxidation of organic matter and the destruction of microbial proteins and enzymes. Additionally, chlorine reacts with inorganic compounds, such as ammonia and sulfides, to form chloramines and other disinfection byproducts.

Proper monitoring and control of chlorine dosage are essential to ensure effective disinfection while mitigating the formation of harmful byproducts.

3.1.1 Chemical Reactions in Chlorine's Role in Water Purification.

In the realm of water purification, chlorine stands as a stalwart guardian against microbial contamination, employing its potent oxidizing properties to neutralize harmful pathogens. The chemistry behind chlorine's efficacy in water treatment unfolds through a series of intricate chemical reactions, each contributing to the eradication of diverse microbial threats. At the heart of chlorine's disinfection mechanism lies its ability to exist in multiple chemical forms, primarily hypochlorous acid (HOCl) and hypochlorite ions (OCl⁻), in equilibrium depending on the pH of the water. This equilibrium, described by the chemical equation:

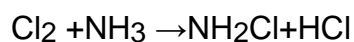


plays a pivotal role in chlorine's effectiveness as a disinfectant. At lower pH values, hypochlorous acid predominates, enhancing its penetration into microbial cell membranes. Conversely, at higher pH values, hypochlorite ions become more prevalent, albeit with diminished disinfectant efficacy compared to hypochlorous acid.

Upon contact with microbial organisms such as bacteria, viruses, and protozoa, free chlorine initiates a cascade of oxidative reactions that dismantle cellular structures and disrupt vital biochemical processes. For instance, hypochlorous acid reacts with cellular proteins, enzymes, and nucleic acids, leading to irreversible damage and microbial inactivation. The chemical equation representing the oxidation of microbial proteins by hypochlorous acid is:



Furthermore, chlorine's disinfection prowess extends beyond direct oxidation to include the formation of disinfection byproducts through reactions with organic and inorganic compounds present in water. Notably, chlorine reacts with ammonia to produce chloramines, which exhibit prolonged disinfection capabilities. The chemical equation representing the formation of monochloramine (NH₂Cl) from chlorine (Cl₂) and ammonia (NH₃) is:



This process is particularly significant in chlorinated water distribution systems, where chloramines serve as residual disinfectants, providing ongoing protection against microbial regrowth.

In essence, chlorine's chemistry orchestrates a symphony of oxidation reactions that safeguard water supplies against microbial contamination. Through its diverse chemical forms and reactive nature, chlorine epitomizes the quintessential disinfectant, preserving public health and ensuring the safety and potability of water resources.

3.2 – Optical Research

The design choices we make are based on the characteristics of the chlorine present in the water sample, which is actually known as hypochlorous acid (chemical formula: HOCL) and hypochlorite ions (chemical formula: OCL⁻). All of the chemistry in section 3.1 was an important foundation to understand the properties of the chemicals we are going to be working with in this project. The absorption spectrum for these two ions is qualitatively demonstrated in figure 1. This tells us what light source we'll need for dissociating the bond with water that enables the reverse osmosis filter mentioned in the project description section of our paper, but for detecting the hypochlorous acid in the water we'll need a different wavelength. The following sections will detail our process for determining how we will detect the free chlorine content in the water and ensure we can accurately find the concentration. We'll need to decide between two separate methods for determining the concentration in the system: spectroscopy and laser attenuation through the water sample. Both of these methods involve knowing the absorption spectrum of free chlorine and as such are similar in terms of final purpose but have differing pros and cons in configurations, price, and complexity. The following sections detail each method and compare them to determine which is best for our purposes.

3.2.1 – Spectroscopy Method for Chlorine Detection

Spectroscopy is commonly done by taking a white light source and shining it through a dispersive element then passing this light through an exit slit. Past the exit slit lies the sample being tested and then a detector that can interpret how much of the light is being absorbed to give the concentration present in the sample based on a known absorption spectrum. The configuration can differ depending on desired result, with the dispersive element possibly being a prism that separates the white light into all of its different wavelengths and then being rotated to "select" the wavelength that passes through the slit. The other common dispersive element used is a diffraction grating, which also separates light into its wavelengths and comes in either reflective form or transmissive form. Reflective gratings reflect the light and change the configuration of the system as a direct result, while

transmissive gratings let the light pass through just like a prism and then separate the light into its constituent wavelengths. The difference between them usually comes down to preference as selecting the correct grating is dependent on a multitude of factors involving efficiency and wavelength range, as well as how one wishes to set up their system.

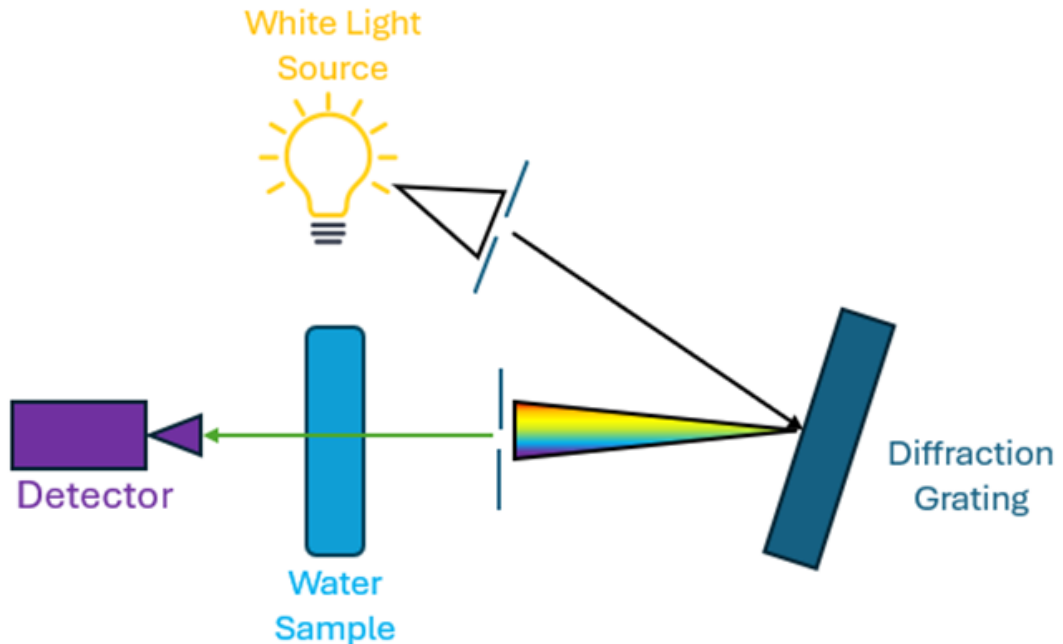


Figure 5. Basic diagram for how spectroscopy with a reflective diffraction grating would work. Note the second slit the light path encounters being used to “select” the desired wavelength.

In this project’s case, we wouldn’t use a white light source as hypochlorous acid responds primarily to light in the UV range, reflected in figure 1, which is invisible to the normal human eye. This has the complication of making alignment considerably more difficult, as well as making the possible laser diodes we use far more expensive as UV lasers tend to be more costly than visible light lasers.

3.2.2 – Laser Attenuation Method for Chlorine Detection

The next method we considered for detecting the chlorine content in our water sample is through attenuation. This is done by selecting a laser wavelength that is absorbed by our desired sample, firing the laser beam through a beamsplitter, and then having two paths: the first leading to a reference photodiode and the second leading through our sample and then a measuring photodiode. Selecting the right beamsplitter enables us to perfectly split the power of the beam by half, which means that we can easily determine how much the laser power is attenuated by comparing the power at the reference photodiode to the power at the measuring

photodiode. By using a known absorption spectrum, we can use the attenuated value to determine how much hypochlorous acid is present in the water sample. This method is simpler to set up and run, only requiring a laser source, a beamsplitter, two lenses, and two photodiodes: one which acts as a control and one which acts as a measure of the laser's attenuation. The simpler set up makes this a viable competitor to the spectroscopy method. Additionally, the total cost is likely comparable to the spectroscopy method. However, this method runs into the same issue that the spectroscopy method runs into, which is that hypochlorous acid absorbs best in the UV range. For this reason, we decided to look into ways that hypochlorous acid could be easier to detect and apply it to either method to determine pros and cons.

3.2.3 – Using Reagents to Ease Detection

Given that the root of issues with detecting hypochlorous acid lies in the fact it absorbs best in the ranges of about 280nm to 350nm, which are in the UV range and make it colorless, we researched some properties of it to see if we could add something to the chlorine and make it appear in the visible range (400nm to 700nm). We came across colorimeter tests, which use a chemical that reacts to the free chlorine present in water to produce a shift in color. This shifted color would enable the use of a visible spectrum laser beam passing through the system to find concentrations, which is far easier to pull off than using a UV light source to complete this task. There are a variety of different ones that can be used to cause this effect, but in this case, we looked at two in particular: DPD and Potassium Iodide.

3.2.3.1 – DPD colorimeter test

DPD (Known formally as *N,N*-diethyl-*p*-phenylenediamine) is a reagent that responds to free chlorine in water and indicates the presence of chlorine by changing to a pink color. It is the test that is most commonly used in the world and was standardized in the 1950s by Arthur Thomas Palin, or Dr. Palin. The test was created as a direct result of chlorination being used to kill biological contaminants in water to purify it of bacteria and other microorganisms, which became increasingly popular worldwide at the time. All of this is stated to drive home the point that this test is well known, easy to perform, and easy to acquire for experimentation at home. With this much background research into it, it's a very appealing option for our project.

The major pros for DPD in our case are twofold: The first major positive lies in that DPD's reaction with free chlorine content in water is directly proportional to how much DPD is present and the second major positive is that there are a variety of options that use DPD which can be purchased on the market at various prices in bulk. A quick Google search reveals that one can get a number of DPD tests in the price range of \$10-\$40. A directly proportional response makes it much easier to

calibrate the system and accurately denote how much free chlorine is present within our water sample. A variety of options on the market reduces the overall cost of this method and makes the colorimeter much more realistic to attain, with most options available offering at least 50 tests, which should be all we need to calibrate the system. Due to the many positives associated with this option, we conclude that this reagent is a viable solution to our desire to bring the free chlorine content into the visible range for analysis and now seek to explore options and weigh the pros and cons of each one.

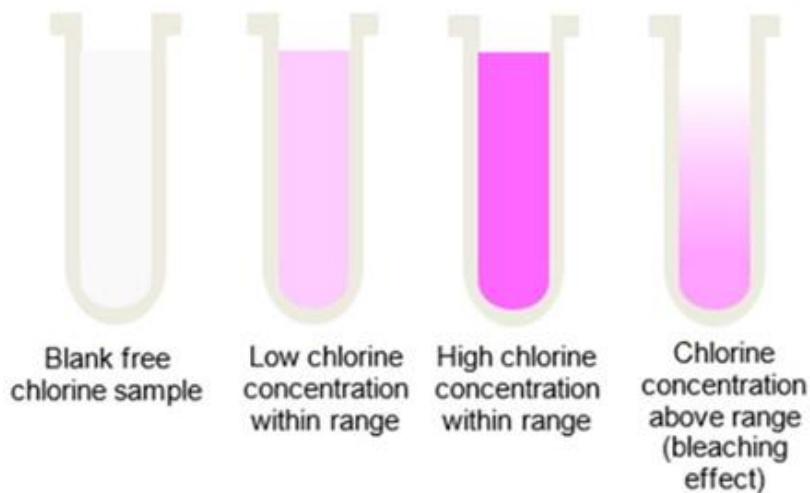


Figure 6. DPD test diagram describing how DPD reacts with chlorine content. A higher concentration results in a darker color, which means the beam would be attenuated more.

Since the DPD test is standardized and has a variety of options, we'd have to select between three types of tests: tablet reagents, liquid reagents, and powder pillows. Tablet reagents are pills which need to be crushed and added to a water sample to produce results. They have a specific dose in them which makes it easier to note how much is present in a water sample. They also have a long shelf life and remain stable at room temperature. However, they take longer than their counterpart, which is liquid reagent tests. Liquid reagent tests are just as accurate as tablet testing but are a bit faster than the latter. However, the tradeoff lies in that liquid additions are more variable, with them being described as "difficult to get the dosage exactly right" [46]. This variability can make it more difficult to be exact and as a direct result is the least safe option for our purposes. Powder pillows are pre-measured amounts of DPD for chlorine testing. They come in the form of little packets that can be ripped open and poured into the sample for testing. Out of all the methods discussed so far, this one seems to take the best parts of the tablet form and make it even better. Since it comes in powdered form, there's no need to crush it and the consistency across all packets is similar, improving our accuracy. Additionally, one can get several packets for under \$50. The tradeoff for this convenience of course comes in the price. It is on average more expensive than

the tablet forms, but never really breaks \$50 unless a great amount of it is purchased at once. Weighing the pros and cons across all forms, it would seem that the powder pillows are the best choice due to its convenience and consistency without an egregious price increase for purchasing in large numbers. For this reason, we have decided that we'll specifically use DPD powder pillows if we select DPD as our primary reagent.

Table 2. Comparison of DPD Reagent Forms

DPD Reagent Forms		
Form Type	Pros	Cons
Liquid Form	1) Can come in prices under \$10. 2) Has best bang-for-buck in pricing across all forms (Assuming perfect dosage each use)	1) Requires refrigeration for storage. 2) Dosage is dependent on the user, and can be less accurate as a direct consequence.
Tablet Form	1) Has a measured dose that is more consistent than liquid form. 2) Has a long shelf life, can be stored in room temperature conditions. 3) Can buy about 100 tablets for just over \$20.	1) More expensive than liquid form on average. 2) Must be crushed before each use and dissolved in a water sample.
Powder Pillow Form	1) Has the measured dose of tablet form, ensuring stability. 2) Has a similar shelf life to the tablet form and remains stable in room temperatures. 3) Can purchase about 100 small powder bags for just under \$40.	1) Most expensive form out of all others, twice as expensive as tablet form and four times as expensive as liquid form.

3.2.3.2 – Potassium Iodide colorimeter test

Potassium Iodide is the other possible reagent that can be added to hypochlorous acid to change the color of water. While it is not standardized like DPD, it is a rather common alternative to it that can detect chlorine content just like its counterpart, with some key differences that we must ponder before selecting it. The color that is produced from this combination is a rather murky brown/orange instead of DPD's pink resultant color. At higher hypochlorous acid concentrations, this brown color can eventually resemble a black color instead. The significance of this lies in that

black naturally absorbs all colors very well, meaning that it would make selecting a wavelength for our laser light source much more trivial. Thus, this reagent's greatest strength is that it would most likely boost our signal greatly as more laser power attenuation would take place after passing through the water sample. Additionally, Potassium Iodide is just as capable as DPD in measuring low to high concentrations of chlorine in water, being capable of detecting a chlorine content range below 0.5ppm and up to 300ppm. However, this choice is not easy particularly because of the major downsides we need to consider before selecting this reagent.

The most immediate concern that comes into play is that Potassium Iodide is not the standardized form of chlorine testing. Since this reagent isn't strictly used for chlorine testing, it can be used for a multitude of purposes such as pharmaceutical treatment for health problems in relation to the thyroid or laboratory purposes. This means that prices are generally much higher across the board and vary from seller to seller. Additionally, this poses a significant risk to our time, as having one of the most important parts of our entire project be more difficult to attain impacts delivery times as well. An even greater concern is that this colorimetric method tests primarily for total chlorine concentrations. The important distinction here is that free chlorine is far easier to remove than total chlorine, due to total chlorine also including chloramines (mentioned in the project description), which are not the primary target of our UV disinfection and could make our results seem less effective overall. Potassium Iodide seems to come primarily in liquid form, with a wide range of prices that can be as low as \$40, which rivals powder pillow DPD in price, or as steep as nearly \$400 when specifically marketed towards chlorine testing in water while in tablet form, which is the best possible form of this reagent for our purposes but is overly expensive for our budget.

3.2.3.3 – Comparison and Final Selection

When selecting between DPD and Potassium Iodide as our preferred reagent, we considered pricing, general effectiveness, ease of access, and all forms of each reagent. The major pros of DPD due to its standardization, relatively cheap pricing per unit, and ease of use makes it a significantly more appealing choice than Potassium Iodide's major drawbacks, which lie in its price and difficulty to obtain. For these summarized reasons, we've decided to use DPD as the reagent to add to our chlorinated water for the laser attenuation section of our project. With this selection, we have solved the issue of how we're going to determine the concentration of free chlorine in the water without spending a high amount of money on detecting it by stressing the absorption in the UV range. As stated in section 3.1.3.1, the best version of DPD to use for our purposes is in the powder pillow packets, which offer great benefits for its price and make the process of adding and analyzing far easier as a result of its consistent amount in each individual packet.

Table 3. Final comparison between reagents

DPD vs. Potassium Iodide		
Reagent	Pros	Cons
DPD	<ul style="list-style-type: none"> 1) Standardization makes pricing and acquiring significantly simpler. 2) Can detect either free chlorine or total chlorine depending on what the user prefers. 	<ul style="list-style-type: none"> 1) Pink coloration makes the signal less prominent in comparison to Potassium Iodide's dark brown.
Potassium Iodide	<ul style="list-style-type: none"> 1) Would have a greater signal than DPD because of the darker color overall. 	<ul style="list-style-type: none"> 1) More expensive than DPD on average. 2) More variation on the market makes getting the right form more difficult. 3) Tests only for total chlorine content, possibly making results more difficult to distinguish due to our target of reducing free chlorine.

3.2.4 – Selection of Light Source

The light source for the detection of the free chlorine in our water sample so we can determine the concentration present is one of the most important parts we need to determine. In order to do so, we first need to find the absorption spectrum of the solution created from a mixture of water, DPD, and hypochlorous acid. This absorption spectrum is explicitly shown in figure 4, which has the wavelength in the x-axis and the absorbance in the y-axis. We can see two distinct peaks here: one in the UV range, seemingly somewhere around 330nm and the second peak takes place in the visible spectrum at about 550nm. The UV range peak appears to also have absorbance increases at wavelengths lower than 300nm, but the shift to 330nm from our original known range of 280nm to 320nm is likely caused by the fact the DPD and hypochlorous acid solution has changed the properties, which is to be expected. The next set of peaks occur in the visible spectrum, with one peak occurring between the ranges of 515nm to 523nm, and the other slightly larger peak occurring between 560nm to 570nm.

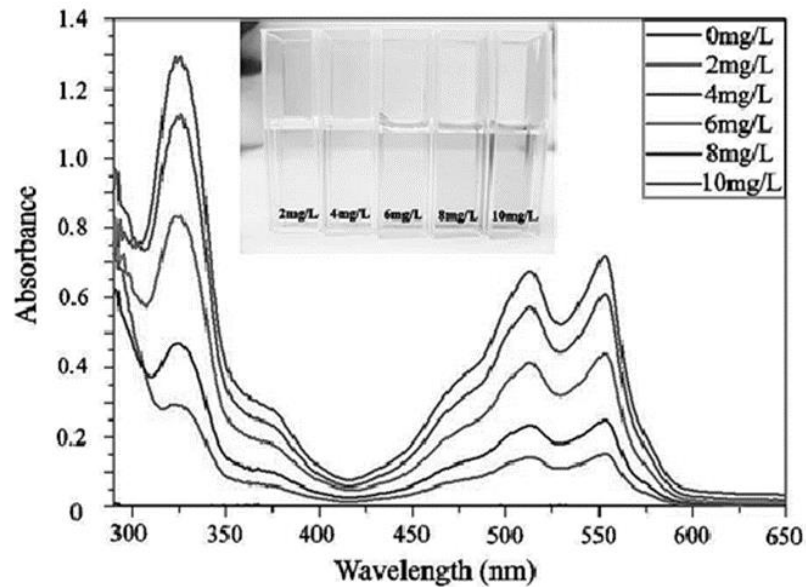


Figure 7. DPD and Free Chlorine solution absorption spectrum. Note how we retain the known peak in the UV spectrum but have a new set of peaks in the visible range (400nm to 700nm).

Based on **Figure 3's** graph, we know that whichever light source we decide on must have a wavelength range be either between 515nm to 523nm or 560nm to 570nm. This falls in the wavelength range for a green laser, which is thankfully somewhat easy to attain in various forms. The forms in question are Light Emitting Diode (LED), laser diode, or a laser pointer. Various vendors sell each kind, so we'll have to compare the pros and cons of each option and determine which to select out of all of them.

3.2.4.1 - Light Emitting Diodes

LEDs are simple components which emit uncollimated light. They are relatively cheap and rather small, which means selecting this component could require us to be conscious of the distance between each part of our system. Light that passes through the water sample must be collimated, which would require the purchase of an additional lens to go directly in front of our LED, placed at the lens' focal length. An additional concern related to LEDs is that the light isn't focused to a point but rather goes outward in a circle around the center, which raises immediate concerns about selecting an LED too powerful resulting in eye injury. While collimated LEDs do exist on the market, the price increase is several times higher and as a result this is simply not an option. One of the best aspects of an LED that isn't true for most other light sources is that depending on the input current, the emitted power varies up to a max. This makes an LED capable of another degree of flexibility no other light source can emulate.

3.2.4.2 - Laser Diodes

Laser diodes are light sources which offer collimated light and are just as prevalent on the market as LEDs. Their average price is much higher than your standard LED but not as high as an LED that comes collimated. They come in a wide range of wavelengths and powers, including the wavelength range we'd like our light source to operate at. They can also be plugged in or powered by battery. Plug-in variations that are compatible with USB are often around \$150 to \$200, with a similar price range for wall outlet plug-in variations, which is just barely within our budget but make usage much simpler as a direct result. The other variations, which have a positive and negative connection, are more involved in set up but are often much cheaper as a result, ranging from \$50 to \$150. It is important to note that despite how expensive this option already is, the wall outlet plug in variations need to have their power supply purchased externally, which is a price increase that definitely needs to be addressed. The strong points of this light source make it a very good contender for our system since it is much safer and comes in a wide variety of forms depending on our specifications, but the steep price associated means we'd need to be very careful in selecting the correct one.

3.2.4.3 - Laser Pointer

Laser pointers are a nice middle ground between LEDs and laser diodes in terms of functionality and price. They can be dirt cheap when bought at the lower quality end, while still retaining solid power, but often sacrificing in the form of the wavelength being less consistent as it shifts by a 10 nm wavelength increase or decrease depending on temperature. In the case of green laser pointers, there is a standardization that works to its detriment for our purposes. Most laser pointers operate at specifically 532nm, which is outside of our optimal wavelengths for our system and could heavily impact results. Additionally, most laser pointers are battery powered, and while some can be continuously charged on USB this is not always the case. The heavy variation of characteristics on the market means that finding the perfect laser pointer for our purposes could be challenging given that most choices that fit our criteria sacrifice one of its supposed pros in comparison to the other options. The laser pointer can have a very good option somewhere on the market, but searching for this perfect option and ensuring it doesn't sacrifice too many positives in comparison can prove to be quite challenging, which makes it an unlikely pick for our purposes.

3.2.4.4 - Comparison

The positives and negatives of each light source are noted once again in the below table, with the highlighted option being the one we choose to move forward with for our system.

Table 4. *Final comparison between light sources*

Light Source	Available in 520nm or 560nm	\$200<	Collimated	Requires Additional Equipment	Available in plug in form
LED	✓	✓	X	✓	X
Laser Diode	✓	X*	✓	✓	✓
Laser Pointer	X	✓	✓	X	✓

**Can be under \$200 but would likely sacrifice aspects of its performance as a result*

3.2.5 – Chlorine Detection Laser Diodes Comparison

Now that we've determined that a laser diode would be best for the chlorine detection section of our system, our next step is to find a laser diode that fits the requirements specified under table 3. Below are three separate kinds of laser diodes, as well as the final selection.

3.2.5.1 – Apinex BES532 520nm Green Laser Module

This laser diode module is rather bare bone but fits our specifications nicely for the price. The primary positive to this module is that it ranges in cost from \$39.50 to \$45.00, increasing in price as output power increases. This is accounting for the fact we don't want more than 10mW of output power from our laser due to the laser power standards discussed later in this paper (Chapter 4, section 2.1). An additional positive is that the price between 1mW and 5mW output power is the exact same \$39.50, which means if one power doesn't suit our requirements, we can return it and get a weaker or stronger version. Since we're splitting the power, the 5mW version is the one we'll consider for this project for now. The wavelength of the laser diode is 520nm, which is the exact wavelength we need for good absorption through the system so we can discern how much free chlorine is present in our water sample. When working with simple components like this that aren't very expensive, we're aware of two primary worries: lifetime and safety of both the product and the personnel around the product. As far as lifetime is concerned, the website states that this laser diode has a minimum lifetime of 5000 hours, which is solid for our purposes. The safety of the product is the next concern, which comes in the form of if it has a countermeasure for common ways to damage laser diodes. The easiest way to damage a laser diode beyond repair is inputting far too much current, over-driving the laser diode. On the website where this laser diode is ordered from, it states that the module is outfitted with an integrated laser driver circuit. The significance of this comes in that a laser driver circuit is included in the module to limit the amount of current that goes into the

laser diode, preventing damage to the laser resonator. As for the safety of people around the system, the laser won't be too powerful to cause damage once the laser beam is split by our system's beamsplitter. Now that we've spoken about the many positives of this choice, next up are the cons.

The main downside to this laser diode module lies in ease of integration. This laser diode isn't connected using a simple USB-C or USB-A. Instead, it's connected using a positive and negative wire, with the user being responsible for ensuring that the input voltage and current don't exceed what the laser diode can handle. While the laser diode does have an integrated laser driver circuit, which as discussed before provides some leniency for going over its limit, the cost of this component convinces us that this circuit likely won't prevent excessive current input. This results in our project needing to be very mindful of the current and voltage the laser diode receives, which the manufacturer states must be less than 500mA and about 3 Volts DC respectively. Any current that is too high into the laser diode risks damaging it very fast, so while the cost is extremely convenient for our purposes, configuring the electronics incorrectly could result in needing to replace the component due to damage. Replacing the component could take some time, as this product ships from Canada, but its not so far away that it'll impede our progress by over a week if we damage the component. Additionally, for a higher shipping price we can express ship it and have it arrive much earlier. Regardless of this downside, the many positives of this laser diode module in performance coupled with its amazingly low price make it a strong contender for our project, provided we can surmount the sensitivity of its input current and voltage and integrate it into our system properly.

3.2.5.2 – Ebay 520nm High Quality Industrial Green Laser Diode

If our previous choice was considered bare bones by our standards, this component is essentially just bone marrow. For just under half the price of the Apinex BES532 Green Laser Module, we'd have a laser diode that is much smaller than the BES532 and has similar performance. The Ebay laser diode is at the same 520nm wavelength as the Apinex laser diode module, which means that it has the same high absorption. With a smaller size, it'd be more compact and certainly much easier to fit into our system. The power comes only at 5mW, with a working current and voltage of 10mA to 30mA and 3 Volts DC respectively. This performance competes with the Apinex laser diode module for less than half the price, which makes it worth considering. However, being cheap in this project can cost greatly in the long run, especially given the very heavy cons that the next paragraph entails.

The immediate concern lies in that the laser diode is a completely exposed component. The Apinex has a casing which contains the more sensitive sections of our laser diode, shielding it from any outside interference. Without an outside casing, the Ebay laser diode is an immediate issue, especially given we're working

with water on this project. There is a remedy to this in the form of the excess filament our group possesses with our 3D printer, but modeling a casing that could shield the Ebay laser diode and 3D printing it is the kind of cost that's most constrained within this project, which is time. Fitting this project within our budget is a game of numbers, but having additional responsibilities which could have an impact on our time, especially if it becomes a back and forth of trial and error, is a risk that we'd have to consider very carefully before selecting this component. The next downside is the working current range. Such a specific working current range can be problematic as over-driving becomes a much more realistic issue within a 20mA range. If damage is dealt to the component, we'd need to replace it, which could easily become a problem later as currently there are only two present within the market that we can purchase. Furthermore, the laser diode comes from Australia, which is an overseas country that could easily take a great amount of time to arrive to the United States of America. Any money that we save with this component we'd pay for heavily in our time, which is priceless. However, there is one more detail which heavily exacerbates all aforementioned issues, and that's what the Ebay reviews reveal about the company that packages and ships this component. Despite Q-BAIHE Australia having a 97.6% positive rating overall on Ebay, which is a very good ratio to have that makes this seller mostly reputable, the customer reviews tell a different story about this component in particular. Due to the sensitive sections of the laser diode being exposed and most of the buyers being from overseas, many customers stated that this part tends to arrive at their destination damaged or unusable. Additionally, the flimsy nature of the component makes it very easy to damage irreparably, which is a serious issue to consider. Regardless, since the performance is similar to the Apinex laser diode module yet costs less than half the price, we're willing to consider this product as our possible laser diode for this project.

3.2.5.3 – Berlin Lasers 520 nm Green Laser Diode Module

This component is the ideal laser diode module for our system. It has the same 5mW output power we seek for our system but with several bonuses. The input voltage for the 5mW Berlin laser diode module is 3 Volts DC, and it has a working current of 500mA at this level. Its dimensions are 26mm diameter by 150mm length wise, which is the largest of all our laser diodes. The lifetime of this product is expected to be about 8000 hours, which is a 60% increase in lifetime in comparison to the Apinex. Given that this component is a module, all sensitive components are carefully shielded by a solid casing, and the connection would be more stable due to this module having a DC input port, which can be easier to integrate into our Arduino. One of the best parts of this component lies in the focus adjustable lens, which lets us control the size of the collimated beam that comes out of this laser diode module. If we need to focus our laser beam to a spot upon our photodiodes, this will trivialize that step and make our design much easier to put together.

The primary cons of this laser diode come in the price, which is multiple times higher than the Apinex at about \$150.00, and the working current, which is 500mA. This working current for the system cannot be supplied by our Arduino, and as such we must remedy it by purchasing a power supply, which increases the price even further. While the website won't state exactly how much more, using Edmund Optics lists additional power supplies for a laser of similar power having a price of about \$57.50, which would increase the price of this laser diode overall to about \$207.50, just over our desired budget of \$200. Shipping is an additional \$20 minimum, which makes this choice very expensive for our purposes.

3.2.5.4 – Comparison of Laser Diodes for Detection of Chlorine

The following table shows a condensed comparison of all laser diode choices, as well as the exact one we'll use for this project.

Table 5. Final comparison between Laser Diodes

Laser Diode	Wavelength	Price	Power	Connection Type	Additional Components Required?
Apinex Laser Diode Module	520nm	\$39.50	5mW	Positive and negative wiring	X
Q-BAIHE Laser Diode	520nm	\$16.66	5mW	Positive and negative wiring	X
Berlin Lasers Laser Diode Module	520nm	\$150 + \$57.50	5mW	DC Output Cable	✓

3.2.6 – Photodiode Selection

Photodiodes have four particular parameters that we need to ponder when selecting one that fits the chlorine detection section of our project: The wavelength it's most responsive to, the max power it can take, the cost, and the active area of the photodiode. In most cases, the max power a photodiode can take is about when a laser beam causes heat where it is focused, which falls into the category of a class IV laser, at 500mW and above of power. As stated in our previous section of laser diode selection and the laser power standards section in chapter 4, we're not planning to have a laser source beyond 10mW in power, which means our photodiodes are only concerned with wavelength response, price, and active area. As for wavelength response, we'd like to have at least 75% from the peak response wavelength since most photodiodes have a wavelength they respond best to. Generally, photodiodes are meant to be purchased in bulk, and as such are not as

heavy upon our budget as other components. We need at least two of whichever photodiode we select, one of which will function as our reference and another which will measure our attenuated power through the sample. Now that we've defined our desired parameters for the photodiode, we'll discuss which one to select.

3.2.6.1 – Vishay BPW21R Photodiode

This photodiode was one of the first we came across on the market, being sold by Digikey, which is a reputable seller. They have a high stock of this component, which makes purchasing multiple rather simple. The price of this component is, on average, higher than most other photodiodes, coming in at \$12.30 for one individual photodiode, which would make the total minimum price \$24.60. The primary positive of this photodiode comes in its large active area. At 7.5mm² of radiant active area, this photodiode can accommodate our focused laser beam very easily. The next parameter to consider is the wavelength response. This photodiode is designed to have peak response at 565 nm, but still works very well at our selected wavelength of 520 nm, reaching about 0.93 relative responsivity. With such a high response, we should have no problems detecting our laser through this photodiode, which makes it a worthy candidate for our system.

3.2.6.2 – Marktech Optoelectronics MTD5052N

The Marktech photodiode trades some of Vishay's positives for a lower price and smaller active area and is also shipped from Digikey. The price of this photodiode is \$7.54, which is nearly half the price of Vishay's photodiode. Additionally, this component is specifically designed to respond best to 525 nm, which according to their datasheet, leads to approximately 100% responsivity at 520 nm, which definitely makes any signal we put through the optical system far easier to detect. However, this lower price tag trades a very important aspect of our photodiode: the radiant active area. The Marktech photodiode only has an active area of 0.57mm², which is an absurdly small area to focus our beam into. The higher responsivity ensures our system will detect a signal, but a small active area will most likely make alignment a more difficult process which could take more time to accommodate. The high responsivity and low price make this component worth considering, despite the abysmally small active area.

3.2.6.3 – EPIGAP OSA Photonics EOPD-525-1-0.9-1

This photodiode is a solid middle ground between the Vishay and Marktech photodiodes. With a slightly larger active area than the Marktech photodiode while having an even lower price, and yet retaining a better response than the Vishay photodiode, this is a very strong contender for our system. The price comes in at \$3.10 per unit, which is under half the price of the Marktech photodiode. Despite the price tag, this photodiode is designed to respond to 525 nm wavelengths, and

as a result has a near 100% response to our target wavelength of 520 nm. The radiant active area is just 0.73mm², which is still rather small for our purposes but is a very mild improvement over the Marktech. However, this size increase is not enough to solve the concern that the Marktech photodiode has, which is that the active area could be problematic when aligning and focusing our beam. As stated before, this could take up time which we need to keep in mind moving forward due to the second semester of our senior design course being particularly short in comparison to the first semester. Overall, the EPIGAP photodiode combines many of the positives of both the Vishay and Marktech photodiodes, but still suffers from the possibility of making our system's alignment much more difficult due to its rather small active area, which makes selecting this photodiode a very tough choice.

3.2.6.4 – Comparison

Below is the table which compares many aspects of the photodiodes discussed previously and selects one based on the pros and cons discussed in detail.

Table 6. Final comparison between Photodiodes

Photodiode	Price	Responsivity at 520 nm Laser Light	Active Area	In Stock
Vishay BPW21R	\$12.30	93%	7.5mm ²	✓
Marktech MTD5052N	\$7.54	~100%	0.57mm ²	✓
EPIGAP EOPD-525-1-0-0.9-1	\$3.10	~100%	0.73mm ²	✓

3.2.7 – Beamsplitter Selection

The beamsplitter we select for our system has quite a few parameters we need to keep in mind when selecting it. The parameters are price, incident surface diameter, approximate power ratio split at 520nm (The first number is the reflected power and the second is the transmitted power through the glass), and coating (the coating dictates what wavelengths the beamsplitter is compatible with). Additionally, beamsplitters come in a variety of shapes, with some being circular or rectangular glass, others being a cube of glass, and on occasion they may come in an unusual shape which requires specific alignment (a wedge or elongated

triangular prism). The preferences we have for this component are as follows: price must be below \$190, the surface diameter should be a minimum of half an inch across the incident surface (this is about 12.7mm), the split ratio at 520nm should be as close to 50:50 as possible, and the coating should be active between 400nm to 700nm. Additionally, a circular or rectangular shape is our preferred shape due to the ease of use in comparison to other shapes, even if this shape could be more easily damaged. There is another aspect to take note of as well, which is the thickness of the component. Any glass surface that our laser beam must travel through causes refraction, which causes a loss in power that we'd need to take note of moving forward. Most sources of beamsplitters have the aforementioned parameters' information upfront, which means that comparing these parameters is a matter of performance vs price, as a good beamsplitter that fits our specifications can be very expensive.

3.2.7.1 – Edmund Optics AR Coated Plate Beamsplitter #13-399

This beamsplitter was a very attractive choice due to its affordable pricing yet solid performance. Edmund Optics is a very reputable seller of optical components which markets this component as affordable yet not compromising in its performance. The Edmund Optics plate beamsplitter is 12.50mmx12.50mm in a rectangular shape and has a coating which is active between 400 nm to 700 nm, both of which are preferred for our system. While the size is about 0.20mm below our preferences, our beam does not exceed 2mm in width and as such we still have 10mm of leeway to align our system and ensure that it travels through the optical design properly, which is more than enough freedom for our purposes. The approximate power ratio split at 520nm is just barely imbalanced, appearing to be somewhere around 45R:55T split ratio, which is enough to still be considerable for our system. Due to the shape of this beamsplitter, we'd need to ensure that the incident angle is exactly 45 degrees, which could have consequences that affect the aforementioned split ratio if misalignment occurs. Another major positive lies in that the beamsplitter itself is about 1mm in thickness, which means it would have negligible results on our laser power once it travels through. The very best positive of this beamsplitter comes in the price, which is a very low \$47.00, and trades little for such a low-price. If an accident occurs and our beamsplitter is damaged in the process of building our system, we can easily purchase another one while remaining beneath our budget's allocated funds for the beamsplitter, which is very important to take note of. If we need to reconsider the shape, the beamsplitter can be purchased with the exact same specifications and price but instead in a circular shape, which grants a great deal of flexibility if this component is chosen. The greatest drawback of this beamsplitter comes from the unusual power split ratio at 520nm, which would make calibration of the system more difficult and time-consuming, but not majorly detrimental. Overall, the price tag in tandem with the very high performance of this component makes it the standard for all upcoming choices.

3.2.7.2 – EMF Corporation Plate Beamsplitter BS-5050-125D

This beamsplitter is rather similar to the Edmund Optics beamsplitter, but boasts a lower price by about 33%, costing \$30.00 instead of \$47.00. The coating of this beamsplitter is active between 400 nm to 700 nm, the size of the beamsplitter is 12.5mm across in a circular shape, and the power split ratio is about 50R:50T at 550nm with an increase or decrease of about $\pm 5\%$ depending on how far the wavelength deviates from 550nm. Additionally, the EMF Corporation beamsplitter has a thickness of 1mm and also comes in a variety of shapes and sizes which retain the same specifications. EMF Corporation is based in New York, which eliminates possible major time constraints due to overseas shipping. While this initially seems like a direct upgrade to the Edmund Optics beamsplitter, its important to note that Edmund Optics lists a direct datasheet of performance across a variety of wavelengths which we can reference when aligning our system and testing output power, whereas EMF Corporation does not have such a datasheet. One could infer that the performance across both components is likely comparable due to the similarities across the component specifications, but this is not an assumption we'd like to make on one of the central components of our optical design. If possible, we'd like to have all this information available so that when aligning our system and reading the power, we have results that are known and referenceable during the setup to streamline the process. Thus, we cautiously list this component as a possible candidate and carefully weigh the lower price against the possibility of more difficulties during the setup and alignment of our optical design due to lack of a data sheet detailing the exact power split ratios at our specific wavelength.

3.2.7.3 – Knight Optical BAE0906 Plate Beamsplitter

This beamsplitter comes at a size of 9mmx9mm in a rectangular shape. This size is much smaller than our desired half-inch beamsplitter, but still gives plenty of leeway for our laser beam when setting up and aligning our system. This beamsplitter has a datasheet accessible on the website which denotes an incredibly impressive performance at 520nm exactly, being a power split ratio of about 49R:51T, better than EMF Corporation and Edmund Optics beamsplitter performances at the same wavelength. The coating is active between 420nm to 680nm, which fits within our preferred range and as a result is not a hindrance to our system despite being a smaller range than our desired parameters. This beamsplitter has a thickness of about 1.1mm, which is slightly higher than the aforementioned beamsplitters and as such likely causes very mild refraction which we'd need to take note of. The greatest positive associated with this component is the absurdly low price of \$17.82, which would be majorly beneficial for our purposes as this low price makes replacement much less costly and as a result clears any issues in relation to possibly going over our budget for the beamsplitter, unless we damage over 10 separate instances of this beamsplitter, which is an incredibly unlikely result. However, this beamsplitter does have a few major

downsides listed on its website which makes selecting it for our system still a consideration, despite the many positives already listed.

Knight Optical is a company based in England, which means any order will likely take much longer to arrive to the United States due to the overseas aspect of the delivery. Thus, what we don't pay in immediate price we pay in both shipping and time of arrival, and as we have discussed in multiple other components, time is our most constraining limitation. Logically, if we select this beamsplitter we would likely order multiple of them to forego having to wait for replacements in the case one or two are damaged. If this was the only downside however, this component would be easily selected. The primary worry if this component is selected lies in the specifications sheet listed on the website. It denotes that the following parameters can be larger or smaller than the listed specifications: length/width, thickness, and flatness. The length and width, as well as the thickness being slightly variable are compromises our system can handle as the possible increase or decrease in all of those parameters is not major enough to offset the advantages of this beamsplitter's performance. However, the flatness is listed on the website to be "not guaranteed." It is somewhat likely that this is just written upon the website as a technicality and that it is not actually a major issue for the quality of the product. The quality of the surface on an optical component is extremely important for performance, and as such this listed possibility is more than worrying for our purposes as the previously mentioned impressive power split ratio at 520nm could be partially offset by an uneven surface on our beamsplitter. For the two reasons discussed in this section, this component is not our outright choice as the risk of having a lower-than-expected performance could be majorly detrimental to our project. Regardless, the possible excellent performance for the price makes Knight Optical's beamsplitter a very alluring choice for our system, which we'll carefully consider.

3.2.7.4 – Thorlabs EBS1 Economy Beamsplitter

Thorlabs is one of the most famous manufacturers of optics components in the world, and as such offers a wide range of optics components with solid performance, all with shipping all over the US easily. This economy beamsplitter has great performance for its price, coming in at \$38.32 total. The coating is effective between 450nm to 650nm, which remains within our desired range and as such is not a problem. The datasheet on the Thorlabs website appears to denote that there is some loss in power through transmission, as the reflectance is about 49% at 520nm, while the transmitted power is only about 47.5%. This beamsplitter is about an inch across (or 25.4mm in diameter) and comes only in a circular shape. The size is twice as large as the set specifications for our system but realistically the constraint on the size was primarily put in place to prevent the price from being too high, and given the low price of this economy beamsplitter, that appears to not be an issue. The thickness is 1mm, which is about on par with all other beamsplitter choices we've considered up until this point. Overall, the only

issue this beamsplitter has in relation to our system is that it loses more power than our other options when transmitting, but for the price this component is a solid pick for our system and as such is worthy of consideration.

3.2.7.5 – Comparison

Below is a table summarizing all the information discussed previously, as well as our selected beamsplitter for this project.

Table 7. Final comparison between Beamsplitters

Beamsplitter	Price	Surface Diameter	Shape	Glass Thickness	Power Split Ratio at 520nm	Location
Edmund Optics #13-399	\$47.00	12.5mm ²	Rectangular Plate	1mm	45R:55T	New Jersey
EMF Corp BS-5050-125D	\$30.00	12.5mm	Circular Plate	1mm	50R:50T ±5	New York
Knight Optical BAE0906	\$17.82	9mm ²	Rectangular Plate	1.1mm	49R:51T	England
Thorlabs EBS1	\$38.32	25.4mm	Circular Plate	1mm	49R:47.5T	New Jersey

3.3 Microcontrollers

Microcontrollers serve as integral components in countless electronic systems, providing the necessary computational power to control and coordinate various tasks within embedded applications. In the context of our senior design project aimed at utilizing lasers for chlorine identification and dissolution, microcontrollers play a vital role in orchestrating the system's functionality. Specifically, they are essential for interfacing with sensors, such as photoresistors, to measure optical loss and infer chlorine presence within the target environment. Moreover, microcontrollers enable seamless communication between the system and a companion mobile application through integrated Wi-Fi connectivity. This communication channel facilitates real-time data exchange, enabling remote monitoring and control of the chlorine detection system. Furthermore, microcontrollers equipped with GPS sensors empower the system with location tracking capabilities, enhancing its utility in diverse operational scenarios. Additionally, microcontrollers can trigger alerts, using integrated speakers, upon detecting elevated chlorine levels, ensuring timely response to potential hazards.

3.3.1 Arduino Uno WiFi Rev2

The Arduino Uno WiFi REV2 offers a blend of familiar Arduino Uno features with the added capability of integrated Wi-Fi connectivity. This makes it a convenient choice for projects requiring wireless communication capabilities, such as interfacing with a mobile application for remote monitoring and control. With the Arduino IDE and extensive Arduino libraries, developers can easily program the Uno WiFi REV2 for a wide range of applications. However, it's essential to note that the Uno WiFi REV2 may have limitations in processing power and memory compared to more advanced microcontrollers like the Raspberry Pi models. Therefore, while suitable for simpler tasks and applications, it may face challenges in handling more complex computations or multitasking requirements.

3.3.2 Arduino Nano ESP32

The Arduino Nano ESP32 is a compact yet powerful microcontroller option, featuring integrated Wi-Fi and Bluetooth connectivity along with a dual-core processor. This combination of features provides increased processing power compared to traditional Arduino boards, making the Nano ESP32 well-suited for projects requiring more computational capabilities. Its small form factor makes it ideal for applications where space is limited, such as embedded systems or wearable devices. However, similar to the Arduino Uno WiFi REV2, the Nano ESP32 may still have limitations in processing power compared to Raspberry Pi models, which could impact its suitability for highly demanding tasks.

3.3.3 Raspberry Pi 4

The Raspberry Pi 4 represents a significant advancement in single-board computing, boasting a quad-core processor, up to 8GB of RAM, and comprehensive connectivity options including built-in Wi-Fi, Bluetooth, and Ethernet. These features make the Raspberry Pi 4 well-equipped to handle demanding tasks and multitasking scenarios, making it a compelling choice for projects requiring extensive data processing and networking capabilities. Its compatibility with various programming languages, operating systems, and software packages further enhances its versatility. However, its larger form factor and potentially higher power consumption may be considerations in certain deployment scenarios where space and energy efficiency are critical.

3.3.4 Raspberry Pi Zero 2W

The Raspberry Pi Zero W offers a compact and cost-effective microcontroller solution with built-in Wi-Fi and Bluetooth connectivity. Despite its diminutive size, the Zero W retains the processing power and capabilities of its larger counterparts,

making it suitable for a variety of projects where space and budget constraints are paramount. Its compatibility with Raspberry Pi accessories and software ecosystem further enhances its appeal for hobbyists, educators, and developers. However, its limited processing capabilities may pose challenges for tasks requiring extensive computation or multitasking, and its small form factor may limit expansion options compared to larger Raspberry Pi models.

3.3.5 Comparison

Table 8. Microcontrollers Comparison

Comparison Features	Arduino Uno WiFi Rev2	Arduino Nano ESP32	Raspberry Pi 4	Raspberry Pi Zero 2W
Processor	ATmega4809	Xtensa dual-core (or single-core) 32-bit LX6 microprocessor	Broadcom BCM2711	Broadcom BCM2710A1
Operating Voltage	5V	3.3V	5.1V	5V
Operating Temperature (°C)	-25 to 70	-25 to 70	0 to 50	-20 to 70
Digital I/O Pins	14	14	40	40
PWM Digital I/O pins	5	All pins (5 simultaneously)	40	40
Analog Input Pins	6	8	-	-
DC current per I/O Pin	20mA	12mA	16mA	16mA
DC Current for 3.3V Pin	50mA	-	16mA	16mA
Flash Memory	48KB	16MB (External Flash)	8GB to 1TB+	8GB to 1TB+

SRAM	6144B	512kB	1GB,2GB,4GB,8GB (DRAM)	512MB(SDRAM)
EEPROM	256B	-	512KB	-
Clock Speed	16MHz	80MHz, 240MHz	1.5GHz	1GHz
Length	68.6mm	45mm	55.88mm	65mm
Width	53.4mm	18mm	86.36mm	30mm
Weight	25g	7g	46g	9g

3.3.6 Choice of Controller and Reason

We have chosen the Arduino Uno WiFi Rev2 over the Arduino Nano ESP32 for our project due to several factors tailored to our specific needs. Firstly, our familiarity with the Uno family of boards provides a seamless transition, leveraging existing knowledge and ensuring ease of use. Since our project exclusively requires Wi-Fi connectivity and not Bluetooth, the Uno WiFi Rev2 perfectly suits our needs without the additional complexity of Bluetooth support. Size constraints are not a concern for our project, and opting for a larger board like the Uno WiFi Rev2 simplifies tasks such as soldering, assembling our system, or designing a secure structure to accommodate the board. Moreover, the extensive compatibility with numerous accessories and products designed for the well-known dimensions of the Uno boards enhances the versatility and convenience of our project setup. Overall, the Arduino Uno WiFi Rev2 aligns perfectly with our project requirements, offering familiarity, simplicity, and ease of integration.

3.3.7 GPS Comparisons

3.3.7.1 MKR GPS Shield

The MKR GPS Shield is an add-on board designed to integrate GPS functionality into Arduino MKR boards. It leverages the u-blox SAM-M8Q GPS module, known for its high sensitivity and fast time-to-first-fix (TTFF). The shield provides precise location data, making it suitable for navigation, tracking, and timing applications. Its compact design and ease of integration with the MKR series enhance its appeal for projects requiring accurate positioning information. Additionally, the MKR GPS Shield supports concurrent reception of GPS and GLONASS, ensuring reliable and robust performance in various environments.

3.3.7.2 Adafruit Ultimate GPS

The Adafruit Ultimate GPS module is a highly reliable and accurate GPS receiver, designed to be easy to use with Arduino and other microcontrollers. It features a high-sensitivity MTK3339 chipset, capable of tracking up to 22 satellites on 66 channels. This module offers fast positioning, with a cold start time of less than 35 seconds and a hot start time of less than one second. Its built-in antenna and additional external antenna connector provide flexibility in installation. The module also supports a wide range of NMEA sentences, making it a versatile choice for various GPS applications, including tracking, navigation, and geofencing.

3.3.7.3 NEO GPS Module

The NEO GPS series, developed by u-blox, includes several high-performance GPS modules, such as the NEO-6, NEO-7, and NEO-M8. These modules are renowned for their excellent accuracy, fast TTFF, and low power consumption. They are capable of tracking multiple GNSS constellations, including GPS, GLONASS, Galileo, and QZSS, depending on the specific model. The NEO GPS modules are compact, making them ideal for space-constrained applications. They are widely used in automotive, personal tracking, and IoT applications due to their robustness and reliability.

3.3.7.4 GPS Selection and Reason

We chose the Adafruit Ultimate GPS module for our senior design project due to its superior compatibility with our existing setup, specifically the Arduino Uno WiFi Rev2. This module's ease of integration and extensive documentation made it a practical choice, ensuring a smoother development process. Its high sensitivity and fast positioning capabilities aligned perfectly with our project's requirements for accurate and reliable GPS data. Furthermore, the module's flexibility, with options for both built-in and external antennas, provided additional adaptability for our design needs. Ultimately, the Adafruit Ultimate GPS stood out as the most suitable option for our project, balancing performance and ease of use.

Table 9. *GPS Module Comparison*

Feature	MKR GPS Shield	Adafruit Ultimate GPS	NEO GPS Module
Compatibility	Designed for Arduino MKR series	Compatible with Arduino Uno WiFi Rev2 in shield form	Compatible with most Arduinos
Libraries	MKR GPS Libraries	Adafruit GPS Library	TinyGPS++
Update Rate	Up to 5Hz	Up to 10Hz	Up to 10Hz
Accuracy	1.5m CEP	1.8m CEP	2.5m CEP
Ease of Use	Easy with Arduino MKR Boards	Easy with Arduino Uno boards	Moderate, additional setup and configuration

3.3.8 Speaker Comparisons

3.3.8.1 Passive Piezo Speaker

A passive piezo speaker is a type of piezoelectric transducer that converts electrical signals into sound waves without any built-in electronics to generate tones. It requires an external driver circuit, such as a microcontroller, to produce sound. This type of speaker is valued for its simplicity, reliability, and efficiency in converting electrical energy into audible sound. Passive piezo speakers are commonly used in applications where size, power consumption, and cost are critical considerations. They are ideal for generating simple tones, alarms, and beeps, making them a versatile choice for many electronic projects.

3.3.8.2 Active Piezo Speaker

An active piezo speaker differs from its passive counterpart by having an internal oscillator circuit that can generate sound independently when powered. It only requires a DC voltage to produce sound, simplifying the design and integration process. Active piezo speakers are convenient for applications where ease of use and quick implementation are essential. They are often employed in alarm systems, timers, and other devices where a consistent tone or beep is needed. While active piezo speakers are straightforward to use, they offer less flexibility in sound customization compared to passive speakers.

3.3.8.3 MP3 Player

An MP3 player module is a more sophisticated audio solution capable of playing pre-recorded audio files stored on external storage devices, such as SD cards or USB drives. These modules typically feature a built-in decoder that can read and play MP3 files, providing high-quality audio output. MP3 player modules are ideal for applications requiring complex audio playback, such as voice messages, music, or sound effects. They are commonly used in projects where rich, dynamic audio is needed, offering a range of functionalities that go beyond simple tones and beeps.

3.3.8.4 Chosen Speaker and Reason

We chose the passive piezo speaker for our senior design project because it offers greater customization compared to an active speaker without requiring additional components like an SD card. The passive speaker allows us to generate a wide range of sounds and tones by controlling the signal from our Arduino Uno WiFi Rev2. This flexibility is crucial for our project, as it enables us to tailor the audio output precisely to our needs. Additionally, the simplicity and reliability of the passive piezo speaker make it an ideal choice for our design, ensuring consistent performance without the complexity of integrating additional hardware.

Table 10. Speaker Comparison

Feature	Passive Piezo Speaker	Active Piezo Speaker	MP3 Player
Power Consumption	Low	Low	High
Complexity	Moderate	Low	High
Control	PWM Signals	Digital Write On/Off	Arduino MP3 Library
Size	Small	Small	Moderate
Cost	Low	Low	Moderate
Flexibility	High	Low	High

3.4 – Hardware Communication Protocols

Communication protocols serve as the backbone of data exchange in various technological systems, ensuring seamless interaction between different hardware components. These protocols dictate the rules and conventions governing the

transmission of data, enabling devices to understand and interpret information exchanged between them. Among the plethora of communication protocols, several stand out for their widespread adoption and versatility. Serial Peripheral Interface (SPI) facilitates synchronous serial communication, ideal for short-distance data transfer between microcontrollers and peripheral devices. Inter-Integrated Circuit (I2C) protocol, on the other hand, offers a low-speed, two-wire communication method commonly utilized in connecting sensors and other peripherals. Universal Asynchronous Receiver-Transmitter (UART) provides asynchronous serial communication, vital for transmitting data between devices over short to medium distances. For more robust and high-speed connections, USB (Universal Serial Bus) protocol reigns supreme, serving as the go-to standard for connecting peripherals to computers and devices. Ethernet protocols, including wired and wireless variants, underpin local and wide area networks, facilitating internet access and local communication in both consumer and industrial settings. In automotive and industrial domains, Controller Area Network (CAN) protocol ensures reliable and efficient communication between microcontrollers and devices. Furthermore, wireless protocols like Bluetooth and Wi-Fi enable seamless connectivity for mobile and IoT devices, catering to a wide range of applications. These communication protocols collectively form the cornerstone of modern technology, enabling the interconnectedness and functionality of diverse hardware ecosystems.

3.4.1 SPI

Serial Peripheral Interface (SPI) stands out as a widely utilized synchronous serial communication protocol, valued for its simplicity and versatility across various electronic systems. SPI facilitates the exchange of data between a master device and one or more peripheral devices, typically microcontrollers, sensors, and memory modules, over short distances. At its core, SPI employs a master-slave architecture, where the master device initiates communication by generating clock pulses and controlling the data transfer process. This protocol typically involves four communication lines: master-out-slave-in (MOSI), master-in-slave-out (MISO), serial clock (SCK), and slave select (SS), enabling bidirectional data transfer and synchronization between devices. One of SPI's key advantages lies in its high-speed operation, making it suitable for applications requiring rapid data exchange, such as sensor readings, memory access, and display interfaces. Additionally, SPI's straightforward implementation and minimal hardware requirements contribute to its widespread adoption in embedded systems and IoT devices. Despite its efficiency, SPI is primarily designed for short-distance communication within a single circuit board or between closely situated devices, limiting its use in scenarios requiring longer transmission distances or multi-node networks. Nonetheless, SPI remains an indispensable tool in the arsenal of communication protocols, offering reliability and performance in a compact and straightforward package.

3.4.2 I2C

Inter-Integrated Circuit (I2C) emerges as a prevalent synchronous serial communication protocol renowned for its simplicity and versatility in connecting multiple peripheral devices to a single microcontroller or CPU. With a master-slave architecture, I2C facilitates bidirectional communication over two wires: a serial data line (SDA) and a serial clock line (SCL). This streamlined approach enables seamless data exchange between devices, making I2C an ideal choice for applications requiring interconnectivity among sensors, EEPROMs, RTCs, and other low-speed peripherals. One of I2C's hallmark features is its multi-master capability, allowing multiple master devices to control the bus and initiate communication, fostering flexibility in system design. Furthermore, I2C supports various data transfer modes, including standard mode (up to 100 kbit/s), fast mode (up to 400 kbit/s), and high-speed mode (up to 3.4 Mbit/s), catering to diverse speed requirements in different applications. Despite its advantages, I2C's susceptibility to bus contention and clock synchronization issues can pose challenges in high-noise environments or when connecting numerous devices over extended distances. Nonetheless, the widespread adoption of I2C in embedded systems, consumer electronics, and IoT devices underscores its reliability, simplicity, and scalability, making it a cornerstone of modern hardware communication protocols.

3.4.3 UART

Universal Asynchronous Receiver-Transmitter (UART) serves as a fundamental asynchronous serial communication protocol, playing a vital role in connecting microcontrollers, peripherals, and various devices over short to medium distances. Unlike synchronous protocols like SPI and I2C, UART operates without a shared clock signal, relying instead on the timing of start and stop bits to synchronize data transmission. This simplicity makes UART well-suited for straightforward point-to-point communication, allowing devices to exchange data reliably without the need for complex clock synchronization mechanisms. UART typically utilizes two data lines: transmit (TX) and receive (RX), enabling bidirectional data transfer between communicating devices. Its versatility and ease of implementation have led to widespread adoption across a broad spectrum of applications, including serial communication between microcontrollers, GPS modules, Bluetooth modules, and sensors. While UART's asynchronous nature simplifies hardware requirements and facilitates compatibility between devices with different clock speeds, it does pose limitations on achievable data transfer rates compared to synchronous protocols. Nonetheless, UART remains a cornerstone of serial communication in embedded systems and IoT devices, offering a reliable and straightforward solution for transmitting data between devices in diverse applications.

3.4.4 USB

Universal Serial Bus (USB) emerges as a ubiquitous and versatile communication protocol, revolutionizing the way devices connect and interact with computers and other host systems. Renowned for its plug-and-play functionality and high-speed data transfer capabilities, USB has become the de facto standard for connecting peripherals, storage devices, input devices, and numerous other gadgets to PCs, laptops, and mobile devices. USB employs a master-slave architecture, with the host device serving as the master controller and peripheral devices acting as slaves. Its hot-swappable nature allows users to connect and disconnect devices without rebooting, providing unparalleled convenience and flexibility. USB supports various data transfer speeds, ranging from the original Low-Speed (1.5 Mbps) and Full-Speed (12 Mbps) modes to the widely adopted High-Speed (480 Mbps), SuperSpeed (5 Gbps), and SuperSpeed+ (10 Gbps) modes, catering to the increasing demand for faster data transfer rates in modern computing environments. Moreover, USB delivers power to connected devices through its bus, eliminating the need for separate power adapters in many cases and simplifying cable management. With its continuous evolution and backward compatibility, USB remains an essential communication protocol, driving innovation in consumer electronics, peripherals, and industrial applications while seamlessly connecting devices and enabling efficient data exchange in a myriad of scenarios.

3.4.5 Bluetooth

Bluetooth stands as a cornerstone wireless communication protocol, facilitating seamless connectivity between a myriad of electronic devices over short distances. Renowned for its versatility, Bluetooth enables data transmission between smartphones, tablets, laptops, headphones, speakers, wearables, and a vast array of IoT devices, without the need for cables or direct line-of-sight connections. Operating in the unlicensed 2.4 GHz ISM band, Bluetooth employs frequency-hopping spread spectrum (FHSS) technology to mitigate interference and ensure robust communication in crowded wireless environments. Bluetooth's low energy variant, Bluetooth Low Energy (BLE), further extends its applicability to battery-powered devices, enabling energy-efficient data transmission for wearables, sensors, and other IoT devices with minimal power consumption. Bluetooth's ease of use, automatic pairing capabilities, and wide compatibility across different platforms have made it a ubiquitous feature in modern electronics, fostering a connected ecosystem where devices seamlessly communicate and collaborate to enhance user experiences. Whether streaming audio, exchanging data, or enabling location-based services, Bluetooth continues to drive innovation and connectivity in consumer electronics, automotive systems, healthcare devices, and smart home applications, empowering users to stay connected and productive in an increasingly wireless world.

Table 11. Hardware Communication Protocols comparison

Feature	SPI	I2C	UART	USB	Bluetooth
Wires	3-4 (MOSI, MISO, SCLK, CS)	2(SDA, SCL)	2(TX, RX)	4+(Power, Ground, Data+)	Varies
Speed	Fastest	Slow-Moderate	Slow-Moderate	Fast	Moderate
Duplex Mode	Full Duplex	Half Duplex	Full Duplex	Full Duplex	Full Duplex
Addressing	Master-Slave	Multi-Master	Point-Point	Device-Host	Device Addressing
Complexity	Simple	Moderate	Simple	Complex	Moderate
Typical Use	Internal communication between chips and PCB	Low-power communication between sensors and microcontroller	Serial communication between devices	Peripheral connections	Wireless communication between devices

3.4.6 Choice of Communication Protocol and Reason

After exploring various communication protocols like SPI, I2C, UART, USB, and Bluetooth to establish a reliable connection between the microcontroller and the GPS module. While each offered its own advantages, UART emerged as the clear favorite for a few compelling reasons. UART is a widely used protocol for serial communication between microcontrollers and peripherals. This widespread adoption translates to a vast library of resources and readily available support, streamlining the integration process for our chosen GPS module. We factored in the compatibility of the Adafruit Ultimate GPS module. Thankfully, the Adafruit Ultimate GPS module seamlessly integrates with UART, eliminating the need for complex workarounds or additional communication modules. By leveraging UART's established infrastructure and the Ultimate GPS module's built-in compatibility, we ensure a smooth and efficient communication channel for our GPS data acquisition.

3.5 – Software Communication Protocol

Seamless data exchange between the mobile application and the microcontroller (Arduino) relies on a well-defined communication protocol. This section delves into several prominent protocols, each with its own strengths and weaknesses, to guide us in selecting the most suitable option for our specific needs. The world of software communication protocols is vast and versatile. Different protocols cater to varying communication requirements, prioritizing factors like speed, reliability, and security. For scenarios where real-time data exchange is paramount, protocols that prioritize speed take center stage, excelling at rapid data transmission for applications like video or audio streaming, though guaranteed delivery and order might not be assured. On the other hand, some applications demand absolute data accuracy. Protocols designed for reliability function like certified mail delivery, ensuring flawless data arrival but at a slightly slower pace. Security becomes a top priority when handling sensitive data. These protocols function like secure envelopes, encrypting the data itself and safeguarding it during transmission, especially over public networks. The software communication protocol ecosystem extends beyond these core functionalities. A specific protocol governs web browsing by dictating how web servers exchange data with web browsers, while another establishes the rules for email communication, ensuring proper routing and delivery of messages. By carefully considering the communication requirements of our project and understanding the characteristics of these prominent protocols, we can make an informed decision. By weighing various factors such as speed, data accuracy, and security and exploring the functionalities offered by various protocols, we can select the most suitable communication language for our senior design project, ensuring smooth and reliable data exchange between the mobile application and the microcontroller.

3.5.1 UDP

UDP (User Datagram Protocol) occupies a unique niche within the software communication protocol landscape. Unlike its counterpart TCP (Transmission Control Protocol), UDP prioritizes swift data transmission over guaranteed delivery. Imagine sending a short text message - information arrives rapidly with minimal formalities, making UDP ideal for real-time applications like video or audio streaming. However, this speed comes at a cost. Unlike a certified letter, UDP doesn't guarantee the data arrives at its destination or arrives in the correct order. Occasional data loss might be imperceptible in a fast-paced video stream, but for critical tasks like file downloads or financial transactions, where even minor inaccuracies can have significant consequences, UDP is not the most suitable choice. This trade-off between speed and reliability makes UDP a strong contender for applications where a smooth flow of information is crucial, even if some data packets are lost along the way. For instance, in a live video conference, a brief stutter caused by missing data packets might be a minor inconvenience, while

waiting for retransmissions in a TCP-based protocol could lead to a more noticeable delay in the conversation. Understanding these strengths and weaknesses is vital when selecting the most appropriate communication protocol for a specific project's needs.

3.5.2 TCP

Within the software communication protocol landscape, TCP (Transmission Control Protocol) stands out for its unwavering commitment to data integrity. Unlike UDP, which prioritizes speed by sending data packets without guaranteed delivery, TCP functions more like a certified mail service. It establishes a secure connection between sender and receiver, fragments data into manageable packets for efficient transmission, and then verifies their receipt with the receiving party. If any packets go missing during transmission, TCP initiates re-transmissions to ensure complete and accurate data delivery. This meticulous approach guarantees data arrives error-free and in the correct order, making TCP a great option for critical tasks where data accuracy is crucial. Financial transactions, file downloads, and other sensitive data transfers all rely on TCP to ensure the information reaches its destination without errors, even over unreliable networks. However, this emphasis on reliability comes at the expense of some speed compared to UDP. TCP's focus on establishing connections, verifying data packets, and re-transmitting missing pieces adds some latency to the communication process. Understanding this trade-off between speed and data fidelity is paramount when selecting the most appropriate communication protocol for a specific project's needs. For applications where real-time data exchange is crucial and occasional data loss might be tolerable, UDP might be a better choice. However, for scenarios where data accuracy is an absolute requirement, TCP remains the go-to protocol for ensuring reliable and error-free data transmission.

3.5.3 SSL/TLS

Secure Sockets Layer/Transport Layer Security (SSL/TLS) protocols play a critical role in safeguarding sensitive information. Functioning similar to a high-security courier service, SSL/TLS encrypts the data itself, adding an extra layer of protection beyond the inherent security measures of the network it traverses. This encryption renders the data unreadable to anyone who intercepts it during transmission, ensuring only the authorized recipient possessing the corresponding decryption key can access the confidential information within. This robust security mechanism is particularly vital when transmitting sensitive data such as login credentials, financial information, or personal health records, especially over public Wi-Fi networks which are inherently more vulnerable to interception attempts. SSL/TLS protocols form the cornerstone of secure communication on the web, guaranteeing the confidentiality of information exchanged on websites like online banking platforms or e-commerce storefronts. While they may introduce a slight

increase in communication latency, the undeniable security benefits far outweigh this consideration. Their application extends beyond web browsing - SSL/TLS protocols are also employed in various secure communication channels, such as email and messaging services, to safeguard the privacy of user interactions. In essence, SSL/TLS protocols act as the silent guardians of the digital world, operating behind the scenes to encrypt and protect sensitive data, fostering a secure environment for online interactions and transactions.

3.5.4 HTTP/HTTPS

Hypertext Transfer Protocol (HTTP) governs communication between web servers and web browsers. It acts as a standardized language, dictating how data is formatted, transmitted, and received. When you visit a website, HTTP fetches the necessary resources, including web pages, images, and scripts, from the server and presents them in a user-friendly format on your browser. This invisible symphony ensures seamless interaction with the vast amount of information stored on the web. HTTP operates in a request-response cycle. The browser initiates a request for a specific resource, identified by a Uniform Resource Locator (URL). The web server processes the request, locates the resource, and sends it back to the browser in a structured format. This protocol facilitates not just static content delivery, but also dynamic interactions. Modern web applications leverage HTTP extensions like HTTPS (secure HTTP) and AJAX (Asynchronous JavaScript and XML) to enable features like secure data transmission and real-time updates within web pages, all relying on the foundation laid by HTTP. In essence, HTTP is the unsung hero behind every web browsing session, orchestrating the communication flow that empowers us to navigate and interact with the boundless information landscape of the internet.

3.5.5 SMTP

The Simple Mail Transfer Protocol (SMTP) plays a critical role in facilitating global email communication. This standardized protocol defines a set of rules for how email clients and servers interact, ensuring the smooth and reliable delivery of messages across vast digital networks. Operating within a client-server model, SMTP governs both the format and transmission of emails between sending and receiving applications. When you compose and send an email, your email client leverages SMTP to establish a secure connection with the outgoing mail server (SMTP server) of your email provider. This server acts as a central hub, verifying the recipient's email address for proper delivery. Once verified, the message embarks on its journey, meticulously routed by the outgoing server to the appropriate incoming mail server (POP3 or IMAP) based on the recipient's domain. Through this intricate process, SMTP orchestrates the efficient transfer of emails across the vast network of servers, ultimately ensuring they arrive safely in the recipient's inbox. SMTP serves as the foundation of this global communication

system, underpinning the exchange of billions of messages daily between individuals and organizations worldwide. While additional protocols like POP3 and IMAP handle message retrieval and storage on the user's device, it is SMTP that orchestrates the initial transmission process. In essence, SMTP acts as the essential foundation for modern email communication, enabling the seamless exchange of information across the globe.

Table 12. Software Communication Protocol Comparison

Feature	UDP	TCP	SSL/TLS	HTTP/HTTPS
Type	Transport Layer	Transport Layer	Security	Application Layer
Connection Oriented	No	Yes	No, relies on TCP for connection	Yes
Reliability	No, packets can be lost, out of order, or duplicated	Yes, guarantees in-order delivery	Not by itself, relies on TCP mechanisms for reliable data delivery	Yes, same as TCP
Error Correction	No	Yes	Not by itself, relies on TCP mechanisms for error correction	Yes, same as TCP
Encryption	No	No	Yes	Yes
Authentication	No	No	Yes	Yes
Typical Use Cases	Real-time applications	File transfers, web browsing, email	Securing communication channels	Transferring web pages and data between web servers and browsers

Port Numbers	Varies	Vaies	Varies, usually 443	80 (HTTP), 443 (HTTPS)
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3.6 – Development Platform

A development platform serves as an environment for creating, testing, and deploying applications. It has a set of tools, libraries, frameworks, and resources for development across diverse platforms and technologies. Many of these platforms offer code editors, advanced debugging tools, and control systems. Additionally, they are designed to support multiple programming languages, providing flexibility and scalability. Examples of development platforms we explored include Android Studios, Xcode, and Flutter.

3.6.1 Android Studios

Android Studio is the official Integrated Development Environment (IDE) for Android app development. It offers a set of tools such as layout editor, code completion, and debugging utilities for creating high quality applications with efficiency. One of the standout features in Android Studios is the built in emulator, which emulates different Androids devices, enabling the developer to test their applications across different platforms. The emulator enhances the development of the applications since it provides real-time feedback of the application performance and behavior. Android Studios supports programming languages such as Java and Kotlin.

3.6.2 Xcode

Xcode is an IDE designed by Apple that enables developers to develop, test, and distribute apps for all Apple platforms. It offers the developer tool for testing, debugging, and optimizing code efficiently. Within Xcode, developers can access frameworks, libraries, and an integrated emulator that allow the developers to test their iOS apps without needing a physical device. The emulator replicates the behavior and features of different iOS devices, enhancing the development process. Additionally, Xcode supports Swift as the programming language for creating iOS apps.

3.6.3 Flutter

Flutter is a development platform that enables developers to build an application across multiple operating systems such as Android and iOS using a single

codebase. It offers a set of tools and collection of widgets, letting the developers build an efficient and appealing user interface. Flutter has a hot reload feature that allows for real time code changes and instant updates for speeding the development process. The primary programming language of Flutter is Dart.

Table 13. Development Platforms Comparison

Comparison Features	Android Studios	Xcode	Flutter
Platform Supports	Android Devices	iOS Devices	Android, iOS, Web, Window
Programming Language	Java & Kotlin	Swift	Dart
Performance	Optimized for Android	Optimized for iOS	Optimized for Cross-Platform
Emulator	Yes	Yes	No
IDE	IntelliJ IDEA-based	Xcode IDE	Visual Studio, Code, IntelliJ IDEA, Android Studios
Hot Reload	Yes	Need to be install	Yes
Widgets	Android Views and Widgets	UIKit	Flutter Widgets

We choose Flutter as our development platform for this mobile application project for several reasons. First, Flutter allows us to create applications that run smoothly across multiple operating systems using just a codebase. While tools like Xcode and Android Studio are limited to their respective platforms. While our current focus is on the Android platform, Flutter ensures that we can expand to iOS in the future without the need to rewrite the entire codebase. Another advantage of Flutter is its accessibility across different devices. While Xcode is exclusive to iOS devices and Android Studio to Windows devices, Flutter can be downloaded and utilized on both platforms, providing flexibility and convenience in our development environment. Finally, Flutter's standout feature is its hot reload capability, enabling us to make real-time updates to our app's interface and functionality without the hassle of restarting the build every time we make a change, saving us time and enhancing the development of the application.

3.7 Tech Stacks

Tech stacks is a collection of technologies, programming languages, and frameworks that work together to build applications. These stacks are typically divided into two components: front-end (client-side) and backend (server-side). The front-end development uses programming languages, frameworks, and scripting languages to build the user interface that clients interact with and perceive. Popular front-end technologies and frameworks include HTML, CSS, JavaScript, React, and Angular. Backend development involves working with databases, server-side frameworks, and programming languages that support the application functionality. Popular backend technologies and frameworks include Node.js, Django, Express.js, MongoDB, and MySQL.

3.7.1 LAMP Stack

LAMP stands for Linux, Apache, MySQL (Structured Query Language), and PHP, is an open-source software for web development. Linux is an open-source operating system that serves as the foundation of LAMP stack. It provides the environment on which the other components of the stack run. Linux is popular because it offers more flexibility and configuration options than some other operating systems. Apache is an open-source web server that processes requests and serves up web assets via HTTP so that the application is accessible to anyone in the public domain over a simple web URL. MySQL is an open-source relational database management system. It is used to store, manage, and retrieve structure data in a database format. MySQL offers features like transactions, indexing, replicating, and stored procedures. PHP open-source scripting language works with Apache to help you create dynamic web pages. It is used to generate dynamic content, interact with databases, handle form, and perform various server-side tasks in web applications.

3.7.2 MERN Stack

MERN stands for MongoDB, Express.js, React, and Node.js, is an open-source framework for web development. MERN is a full-stack application since it has the ability to develop the front-end and the back end using the same programming language. MongoDB is a scalable, flexible NoSQL document database platform designed to overcome the relational databases approach and the limitations of other NoSQL solutions. Unlike other databases, MongoDB documents (data) are stored in BSON format, which is a binary-encoded JSON, allowing for a much faster traversal. The documents in a collection (table) can have different fields and data types, making it a dynamic schema. It also offers features such as automatic sharding for horizontal scaling, built-in replication, and flexible querying. Express.js is the most popular web framework for Node.js. It is designed for building web applications and APIs (Application Programming Interface) and has been called

the de facto standard server framework for Node.js. It provides a set of features for handling HTTP requests, routing, middleware integration, and managing server-side logic. Node.js is an open-source, cross-platform, JavaScript runtime environment that executes JavaScript code outside of a web browser. It is built on the V8 JavaScript engine providing high performance and scalability for server-side applications. Node.js uses an event-driven, single-threaded I/O model making it efficient for handling concurrent operations such as files systems operations, networking, and database interactions.

3.7.3 MEAN Stack

The MEAN stack, an acronym for MongoDB, Express.js, AngularJS (or Angular), and Node.js, represents a powerful and popular combination of technologies for building dynamic web applications. MongoDB serves as the NoSQL database, providing a flexible and scalable storage solution for handling diverse data types. Express.js, a minimalist web application framework for Node.js, simplifies server-side development by enabling efficient routing, middleware integration, and request handling. AngularJS or Angular, depending on the version used, facilitates front-end development by providing a robust framework for building dynamic, single-page applications with enhanced interactivity and user experience. Finally, Node.js, a server-side JavaScript runtime environment, powers the entire stack, enabling JavaScript to be used across the full application stack, from client to server. Together, the MEAN stack offers a seamless and cohesive development experience, allowing developers to build feature-rich, real-time web applications efficiently.

Table 14. Tech Stack Comparison

Comparison Features	LAMP	MERN	MEAN
Components	Linux, Apache, MySQL, PHP/Python	MongoDB, Express.js, React.js, Node.js	MongoDB, Express.js, React.js, Node.js
Server-side Backend	PHP/Python	Node.js	Node.js
Database	MySQL	MongoDB	MongoDB
Programming Language	JavaScript, Python	JavaScript	JavaScript

Scripting/Style Sheet Language	HTML, CSS, PHP, MySQL	N/A	N/A
Cost	Open-Source	Free version/ Paid version	Free version/ Paid version
Web Server	Apache	Express.js	Express.js
Frontend	N/A	React.js	Angular

We selected the MERN stack as our backend tech stack for our project mobile application for several advantages. MongoDB is an ideal choice for our project since we will be working primarily with the user information and credentials and do not rely on relational data, making a NoSQL database a great match for us. Express.js will play a crucial role in simplifying backend development. Its structure allows us to organize all backend code efficiently with a single file code, improving code organization. Node.js lets us benefit through its npm (Node Package Manager) packages. These packages can be easily installed into our project and facilitate the creation of API, integration with MongoDB, and using multiple packages for enhancing functionality and efficiency.

3.8 Programming Languages

Programming languages are the foundation of modern software development, providing developers with the tools and syntax needed to instruct computers to perform specific tasks. With an abundance of languages available, each tailored to different use cases and domains, programming languages serve as the primary means of communication between humans and computers. From low-level languages like assembly and C, which offer direct control over hardware and system resources, to high-level languages like Python and JavaScript, which prioritize readability and ease of use, there exists a vast spectrum of languages to suit diverse programming needs. Furthermore, languages like Java, C++, and C# are renowned for their versatility and performance, making them popular choices for building large-scale applications and systems. With the rapid advancement of technology, new languages continue to emerge, each with its own unique features and capabilities, shaping the ever-evolving landscape of software development. Ultimately, the choice of programming language depends on factors such as project requirements, developer expertise, and performance considerations, with each language offering its own set of strengths and trade-offs. This section will go

into detail about the languages we are considering and comparing to develop our frontend, backend, and microcontroller with.

3.8.1 Javascript

JavaScript is a fundamental programming language for web and app development, widely renowned for its versatility and flexibility. In the realm of app development, JavaScript plays an important role in both frontend and backend development, making it a preferred choice for building modern applications. On the frontend, JavaScript is used to create dynamic and interactive user interfaces, enabling developers to build engaging experiences that respond to user input and events. Its asynchronous nature and event-driven architecture make it particularly well-suited for handling user interactions and updating the UI in real-time. Additionally, with the advent of frameworks like React, Angular, and Vue.js, JavaScript has become indispensable for building robust frontend applications that deliver high performance and seamless user experiences across various devices and platforms. On the backend, JavaScript's versatility extends beyond the browser, thanks to platforms like Node.js. Node.js allows developers to run JavaScript code server-side, enabling them to build scalable and efficient backend services and APIs. Javascript is a likely language that we will focus on due to its popularity and use with tech stacks such as MERN and MEAN.

3.8.2 Typescript

TypeScript is a superset of JavaScript developed by Microsoft that adds optional static typing and other advanced features to the language. TypeScript extends JavaScript by incorporating features such as type annotations, interfaces, generics, and advanced object-oriented programming constructs, making it particularly attractive for large-scale applications and projects requiring increased maintainability and code organization. By enabling developers to catch errors at compile-time and provide clearer documentation through type annotations, TypeScript enhances code quality and developer productivity. Additionally, TypeScript integrates seamlessly with existing JavaScript codebases and toolchains, allowing for gradual adoption and interoperability with popular JavaScript frameworks and libraries. With its strong typing system, powerful tooling support, and growing community adoption, TypeScript has emerged as a valuable tool for building robust, scalable web applications and enterprise-level software solutions. Being similar to Javascript while having more features makes Typescript a potential language to focus our frontend and backend development on.

3.8.3 C++

C++ is a high-level programming language renowned for its versatility, efficiency, and performance across a wide range of applications. Developed as an extension

of the C programming language, C++ introduces object-oriented programming (OOP) features such as classes, inheritance, polymorphism, and encapsulation, enabling developers to write modular, reusable code and build complex software systems. With its rich standard library and support for low-level programming constructs, C++ is well-suited for developing system software, operating systems, embedded systems, and performance-critical applications like video games and real-time simulations. Its strong typing system and compile-time checks contribute to robust and secure software development, while features like templates and generics offer flexibility and extensibility. Additionally, C++ compilers are available on a wide range of platforms, making it a versatile choice for cross-platform development. Despite its complexity, C++ remains a popular language among developers for its power, efficiency, and ability to produce high-performance software solutions. C++ can be used to develop on Raspberry Pi and Arduino microcontrollers which makes C++ a potential language to consider.

3.8.4 Python

Python is a high-level programming language celebrated for its simplicity, versatility, and widespread adoption across various domains. Python prioritizes readability and ease of use, making it an ideal choice for beginners and experienced developers alike. With its clean and concise syntax, Python emphasizes code readability and encourages developers to write elegant, efficient code. Python's extensive standard library and vibrant ecosystem of third-party packages provide developers with a vast array of tools and resources to tackle diverse tasks, from web development and data analysis to machine learning and automation. Known for its dynamic typing, automatic memory management, and cross-platform compatibility, Python offers flexibility and ease of use, enabling developers to quickly prototype ideas and build scalable, maintainable software solutions. Overall, Python's combination of simplicity, power, and community support has solidified its position as one of the most popular and beloved programming languages in the world. Python can be used to develop on Raspberry Pi and Arduino microcontrollers which makes this a potential language to consider.

Table 15. *Programming Language Comparison*

Feature	JavaScript	TypeScript	Python	C++
Type System	Dynamically Typed	Statically Typed	Dynamically Typed	Statically Typed

Use Cases	Web Development, App Development, Frontend and Backend	Web Development, App Development, Frontend and Backend	Web Development, Backend, Microcontrollers	Microcontrollers, Systems Programming
Performance	Slower compared to C++	Slower compared to C++, potential better performance than JavaScript	Slower compared to C++, potential better performance than Javascript with optimized libraries	Fast and Efficient
Memory Management	Garbage Collected	Garbage Collected	Garbage Collected	Manual Memory management

3.9 Email API

Email API is a tool that developers use to integrate email functionality into their applications. These API provide a set of protocols, rules, and tools that enable communication between different software applications and email servers. They allow developers to send and receive email programmatically and perform various email-related tasks such as creating drafts, scheduling emails, and handling attachments. Email APIs are essential for creating email automation systems, enhancing user experience, and streamlining communication processes in modern applications.

There are three main types of email API: transactional, marketing, Simple Mail Transfer Protocol (SMTP). Transactional email API are designed for sending personalized one to one email to users within an application, such as registration, password reset, order confirmation, and notification. This API ensures timely and relevant communication with users. Marketing email API focuses on sending bulk emails to targeted audiences for promotional purposes, such as newsletters, product announcements, and promotional offers. SMTP provides developers with low level control over the email sending process, allowing for direct communication with SMTP servers to handle authentication, messages formatting, and attachments.

3.9.1 SendGrid

SendGrid is a cloud-based email delivery service known for its capability in sending both transactional and marketing emails. Through its API, developers can smoothly integrate email sending, tracking, and management functionalities into their applications. The SendGrid API lets developers create and send emails programmatically, manage email templates efficiently, track the delivery status of email, and analyze metrics related to email engagement. One of the features of the SendGrid API is that it supports multiple programming languages, ensuring compatibility with a wide range of development environments. Also, SendGrid provides a diverse documentation and code example, simplifying the integration process and allowing developers to create the code efficiently.

3.9.2 Mailchimp

Mailchimp is a marketing automation platform and email marketing service. It allows users to create, send and manage email campaigns, newsletters, and automated messages to their subscribers. Mailchimp offers a range of features including customizable email template, audience segmentation, marketing automations workflows, analytics, and integrations with various third-party platforms. One of Mailchimp notable features is its user-friendly interface that makes it easy for businesses and individuals to design and send professional emails. It also provides tools for managing subscriber lists and tracking engagement metrics such as open rates.

3.9.3 Gmail API

The Gmail API is a RESTful API (Representational State Transfer Application Programming Interface) that allows developers to access and manage Gmail mailbox data programmatically. It provides functionalities such as sending and receiving emails, managing labels and filters, searching for messages, and accessing attachments. Developers can use the Gmail API to integrate email capabilities into their applications, such as creating drafts, scheduling emails, and handling email attachments programmatically. The API supports OAuth 2.0 authentication for secure access to Gmail data and offers comprehensive documentation, client libraries, and code samples for developers to get started quickly.

Table 16. *Email API Comparison*

Comparison Features	SendGrid	Mailchimp	Gmail API
Email Type	Supports transactional and marketing emails.	Primarily focused on email marketing campaigns.	Designed for managing personal and business email accounts.
Functionality	Send and track emails, manage templates, analyze metrics.	Manage subscriber lists, create/send campaigns, segment subscribers.	Access mailbox data, send/receive emails, manage labels/filters
Integration	Integrates easily into applications with SDKs	Offers developer tools, libraries, and extensive API documentation.	Provides OAuth 2.0 authentication, client libraries, and code samples for integration.
Developer Support	Strong developer support with code examples, tutorials, and community forums.	Comprehensive developer resources, including API guides, libraries, and support.	Offers detailed documentation, client libraries, and OAuth 2.0 authentication for secure access.
Pricing	Offers various pricing plans based on email volume and features.	Pricing based on the number of subscribers and features required.	Free for limited usage, with pricing based on API usage and features for larger-scale applications.

Chapter 4 - Standards and Design Constraints

4.1 Standards

There are important standards that must be considered such as laser power standards, software testing standards, and PCB standards. Laser power standards provide essential guidelines for the safe use of lasers, outlining parameters such as power output, wavelength, and safety features to prevent accidental exposure and ensure user safety. Adhering to these standards is paramount in our project, given the use of lasers. Software testing standards establish protocols for the evaluation of software functionality, reliability, and security. By following recognized testing standards, such as those outlined by organizations like the IEEE (Institute of Electrical and Electronics Engineers) and ISO (International Organization for Standardization), we can ensure the robustness and integrity of the software components integral to our project's operation. Additionally, adherence to PCB standards is crucial in ensuring the quality, reliability, and compatibility of our circuit board designs. These standards outline specifications for factors such as layout, materials, and manufacturing processes, facilitating efficient production and interoperability of PCBs within our project. By aligning with laser pointer standards, software testing standards, and PCB standards, we uphold best practices in safety, quality, and performance, thereby enhancing the overall success and effectiveness of our project.

4.1.1 Laser Power Standards

Laser power safety is a concern we need to ponder when designing our system to ensure the user isn't damaged by our product. Before we discuss power standards, one factor immediately makes our product much more dangerous to the eyes. The laser beam for the detection section of our project has a wavelength between 515nm to 570nm, which falls mostly in the green color range. The human eye collects images at the retina, which is the back surface of your eye. This retina is composed of little rods and cones, which are responsible for vision in dark and illuminated environments respectively. Vision is focused in an area known as the fovea, which is very important for ensuring the image is sharp and easy to see. Due to the spectrum of our eye, as shown in **Figure 14** below, we are most sensitive to green light specifically. This means we have to be particularly mindful about how we direct the laser beam in our system to ensure the user isn't damaged by the detection section of our product. The simplest way to ensure this concern is minimized is by having our components completely immovable once setup, which can be done by 3D printing casing for each component. This is already planned to be in our design process due to one of our group members owning a 3D printer and having an excess of filament for use in this project.

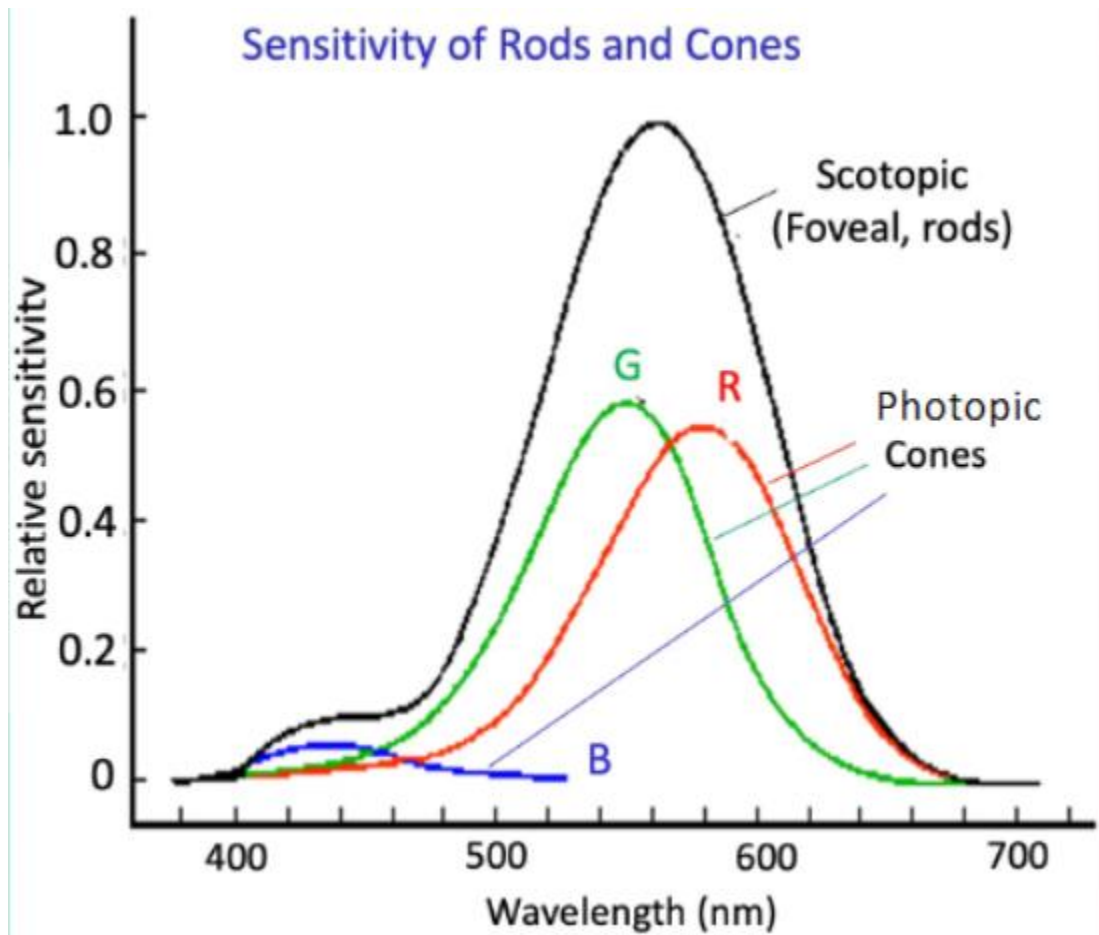


Figure 8. Sensitivity of the human retina. Notice how relative sensitivity peaks around the green color and is just above red. This minor increase is very notable in practice.

Given that whatever power we select for our system must take into account that green light is particularly sensitive for the human eye, our next step here is to determine what power output for our laser source is safe. To this end, we researched standards in relation to laser power and what thresholds become dangerous to the human eye, which is summarized in figure 2 below.

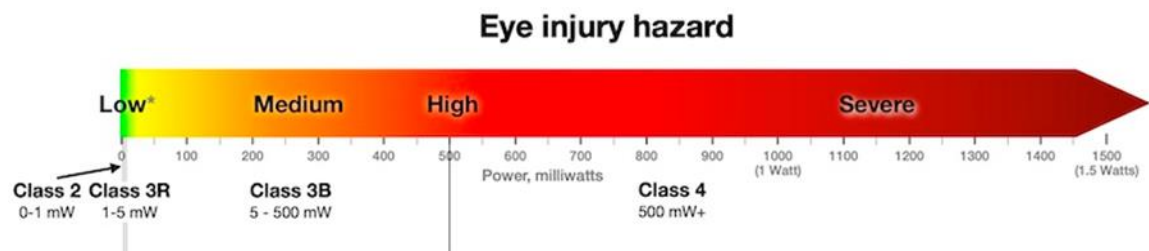


Figure 9. Eye injury hazard as laser power increases. While this chart may state that medium risk is only present around 100mW and beyond, experience with

lasers from the optics students suggests that even 10mW of laser power can be harmful to the eyes when shined on a mostly opaque surface.

This figure makes laser power seem much less dangerous than it truly is. Laser classifications take into account the effect of laser light when observed on a non-reflective surface and when shined directly at one's eye. At about class 3R, or 5mW laser power, the human eye can no longer use its reflex of closing upon exposure to overly bright light to prevent damage if the laser light is shined directly into the pupil. However, even when not shined directly into the eye this laser power has repercussions. Experiences in the lab from the photonics students makes it clear that at 5mW of power, laser light at green wavelengths shined on a non-reflective surface can still hurt the eyes, usually causing what is known as an "afterimage". Afterimages are what occur when one looks at a bright light for a bit too long, causing dark spots in one's vision. While this effect disappears after a few minutes and is only really a bit bothersome, 5mW of light already has pronounced effects on one's vision, which makes any laser power beyond 5mW possibly dangerous, exacerbated by the previously discussed sensitivity to green light human eyes exhibit. For these reasons, we've decided to avoid using laser sources with output power beyond 5mW, as it could pose a risk to our system's user, regardless of how many safety precautions we take to prevent this result.

The configuration of the detection section of our project assists in this since our system splits the laser source and effectively causes the shined light to reach two separate locations at about half the power. At about 2.5mW, green laser light mostly loses the ability to cause afterimages, though prolonged staring at the light on a non-reflective surface still causes afterimages eventually. Additionally, if the laser light somehow shines at the eye directly, the human reflex of closing the eyes upon viewing overly intense light can easily protect one's vision. Splitting the light enables us to expand our possible laser power from 3mW to 9mW, since we can split the power and ensure that it's mostly safe for human viewing, though we're planning to enclose most of our system regardless.

How this pertains to our Project

In our senior design project focused on detecting chlorine concentrations in water samples, understanding laser safety standards is crucial. Laser safety standards, such as ANSI Z136.1, provide essential guidelines for handling and operating laser systems safely. While lasers might not be the main focus of our project, they could potentially be incorporated into advanced detection methods or spectroscopic techniques for chlorine analysis. Ensuring compliance with laser safety standards is vital to protect our team members and to safely integrate any laser technologies we may use.

Additionally, as we aim to innovate and potentially incorporate advanced detection methods or spectroscopic techniques into our chlorine analysis, understanding and adhering to laser safety standards becomes even more relevant. These

standards guide us in the proper handling, operation, and control of laser systems, minimizing risks associated with laser radiation exposure. By incorporating these safety standards into our project design and implementation, we demonstrate our commitment to protecting our team members and achieving accurate and reliable chlorine detection in water samples while exploring advanced technological solutions.

4.1.2 Software Testing Standards

Adherence to software testing standards is key to ensure the reliability, functionality, and security of our software components. Given the critical role of software in monitoring water quality and enabling user interaction through the mobile app, rigorous testing protocols must be followed. This entails testing software functionalities such as control algorithms, sensor data processing, user interface interactions, and data communication protocols. Additionally, software testing standards, such as those outlined by organizations like the IEEE (Institute of Electrical and Electronics Engineers) and ISO (International Organization for Standardization), provide guidelines for testing methodologies, test coverage, test documentation, and quality assurance practices. By adhering to recognized software testing standards and conducting thorough testing throughout the software development lifecycle, we can ensure the robustness, reliability, and safety of our software components, thereby enhancing the overall effectiveness and success of our project.

How this pertains to our Project

Our project's success hinges on the seamless interaction between a mobile app and an Arduino Uno controlling a laser and monitoring water quality via WiFi. This underscores the critical role of software testing. The software not only facilitates user interaction through the mobile app but also shoulders critical tasks like managing the laser and processing sensor data. To ensure a robust and reliable system, we must implement rigorous software testing protocols.

4.1.3 PCB Standards

Ensuring consistent quality and functionality throughout the entire production process of Printed Circuit Boards (PCBs) is critical for modern electronics. This is where industry-established PCB standards come into play. These comprehensive guidelines serve as a universal language, dictating best practices across every stage of a PCB's lifecycle, from the initial design conception to final assembly.

Leading organizations like the IPC (Association Connecting Electronics Industries) play a vital role in developing and maintaining these crucial standards. Their extensive library encompasses a wide range of aspects, including critical design rules. These rules meticulously define parameters like trace width, conductor

spacing, and layer-specific material selection. Essentially, they function as a well-defined recipe for crafting a PCB that is not only functional but also exhibits long-term reliability. Furthermore, standardized file formats established by the IPC ensure seamless data exchange. This fosters clear communication and minimizes the risk of errors during production. The reach of PCB standards extends beyond the design phase, encompassing the assembly process as well. Stringent requirements for soldering electrical components onto the PCB are outlined, guaranteeing the creation of robust electrical connections that can withstand the test of time. Additionally, these standards define comprehensive inspection procedures. This meticulous approach ensures that only defect-free, high-quality PCBs reach the end user. By adhering to these established guidelines, manufacturers can consistently deliver PCBs that flawlessly meet design specifications and deliver optimal performance within the intended application. In essence, PCB standards serve as the cornerstone for achieving quality, reliability, and consistent performance in the ever-evolving realm of electronic devices.

How this pertains to our Project

Standardization offers numerous benefits for our project. Crucially, well-defined design rules govern aspects like trace width, conductor spacing, and material selection. These meticulous specifications function as a recipe for crafting a PCB that is not only functional but also exhibits long-term reliability. Furthermore, standardized file formats ensure seamless data exchange between design and manufacturing stages, minimizing errors caused by incompatible formats. The reach of PCB standards extends beyond design, dictating stringent requirements for soldering electrical components. This ensures robust electrical connections that can withstand the test of time. Additionally, these standards define comprehensive inspection procedures. This meticulous approach guarantees that only defect-free, high-quality PCBs reach us, minimizing the risk of malfunctions due to faulty boards. By adhering to these established guidelines, we can achieve a well-functioning, reliable, and high-performing final product while reducing the risk of errors and delays during manufacturing, ultimately leading to a more successful project.

4.1.4 Hardware Communication Protocol Standards

In the realm of electronic design, standardized hardware communication protocols play a critical role in ensuring the smooth and reliable exchange of data between a multitude of devices. These protocols function as a well-defined language, meticulously crafted by organizations like the Institute of Electrical and Electronics Engineers (IEEE). Their standardized specifications guarantee seamless interoperability. This fosters a cohesive environment where a USB flash drive, adhering to the USB protocol, can effortlessly exchange data with any computer programmed to understand the same language.

The selection of an appropriate protocol hinges on the specific application. High-speed data transfer between a computer and its peripherals necessitates a robust protocol like USB, capable of transmitting large volumes of data efficiently. On the other hand, low-power communication between miniature sensors and microcontrollers might leverage I2C, a streamlined protocol optimized for energy-efficient data exchange. Beyond facilitating seamless device interoperability, standardized communication protocols offer a multitude of advantages for the engineering community. Adherence to established protocols simplifies the design process. Imagine the complexities involved in designing a microcontroller from the ground up, requiring compatibility with every unique sensor protocol in existence. Standardized protocols eliminate this hurdle, enabling engineers to focus their ingenuity on the innovative aspects of their projects. Furthermore, these protocols cultivate a well-oiled ecosystem of interchangeable parts. A sensor designed for I2C communication will likely function flawlessly with any microcontroller that adheres to the same I2C standard, regardless of the manufacturer. This interchangeability translates to greater flexibility and efficiency.

How this pertains to our Project

In our senior design project, leveraging standardized hardware communication protocols is paramount for ensuring reliable data exchange between various components. This aligns with the overarching principle of fostering a well-oiled system, similar to how established engineering practices promote seamless interaction. These protocols, meticulously crafted by organizations like the IEEE, function as a universal language, akin to the standardized file formats used in PCB design. This ensures seamless interoperability, akin to how a USB flash drive can effortlessly exchange data with any compatible computer. The selection of an appropriate protocol hinges on the specific application. For our project, protocols like USB or Bluetooth can be utilized to establish reliable communication between the Arduino Uno and the mobile app. This ensures smooth data flow, similar to how a well-defined language enables clear communication. By adhering to established protocols, we can streamline the design process, eliminating the need to develop custom communication methods. In essence, by embracing standardized hardware communication protocols, we aim to achieve a well-functioning, reliable, and efficient system for data exchange within our project. This aligns with the broader engineering principle of promoting seamless interaction between components, ultimately contributing to a more successful outcome.

4.1.5 3D Printing Standards

The prevailing standard in 3D printing is **Y14.46-2022**, released by the American Society of Mechanical Engineers. This Additive Manufacturing guideline focuses on standardizing 3D printing materials, parameters, and techniques. These standards provide flexibility for adjustments according to design requirements and the continuous advancements in 3D printing technology. 3D printing enables the

creation of parts from various plastics or metals tailored to meet product specifications. While some 3D printers prioritize accuracy at the expense of speed and material efficiency, others prioritize speed and material conservation but may sacrifice precision.

Material extrusion is the most common 3D printing method, where material is pushed through a heated nozzle to become malleable during extrusion. The extruder moves across a build plate to construct each layer of the design. After completing a layer, the build plate descends or the extruder rises to begin the next layer. Alternatively, binder jetting involves applying a binding agent to a thin layer of metal, sand, or ceramics, which solidifies based on the design input. The build plate lowers to apply more powder for each subsequent layer until the design is fully formed.

How this pertains to our Project

In our senior design project, adhering to the **Y14.46-2022** standard set by the American Society of Mechanical Engineers is crucial, especially given that a significant portion of our project relies on 3D printing to achieve higher precision. This standardization in Additive Manufacturing provides a structured approach to selecting materials, defining parameters, and employing techniques that align with our project's requirements. By following these guidelines, we can ensure that the 3D-printed components, whether using material extrusion or binder jetting methods, meet the necessary quality and performance standards. Material extrusion's layer-by-layer approach allows us to construct intricate parts with the required accuracy, while binder jetting's versatility in handling various materials offers flexibility in component design. These 3D printing methods enable us to create tailored parts from plastics or metals that are not only precise but also optimized for our chlorine concentration analyzer's functionality and reliability. Thus, integrating the **Y14.46-2022** standard into our 3D printing processes reinforces our commitment to achieving high precision and quality in our project's implementation.

4.1.6 Chlorine Concentration Standards

EPA Method 330.5 stands as a pivotal guideline established by the U.S. Environmental Protection Agency (EPA) to measure total residual chlorine (TRC) in diverse water sources. Employing colorimetric or amperometric titration techniques, this method offers a reliable means to assess both free and combined chlorine concentrations in water samples. This assessment is paramount for safeguarding drinking water quality, ensuring the effectiveness of chlorine disinfection processes, and guiding our perception of dangerous chlorine levels. Adhering to this method is not just a procedural necessity but a vital step for water treatment facilities to demonstrate compliance with stringent regulatory standards and maintain public health.

In the context of our senior design project, **EPA Method 330.5** holds significant relevance. By incorporating this method into our project framework, we aim to create a robust system for water quality testing and treatment optimization. Accurate measurement of chlorine residuals enables us to ensure water safety. Moreover, implementing this EPA-approved method provides us with invaluable hands-on experience in utilizing industry-standard water testing techniques, thereby bridging the gap between theoretical knowledge and practical application.

Furthermore, our project's focus on **EPA Method 330.5** serves a broader purpose beyond academic exploration. It positions us at the forefront of advancements in water quality monitoring technologies and practices. By enhancing our understanding of chlorine measuring processes, we are better equipped to address real-world challenges in environmental engineering, water treatment, and public health. This practical experience not only enriches our educational journey but also prepares us for future careers where our expertise can contribute to ensuring safe and sustainable water resources for communities.

How this pertains to our Project

In our senior design project focused on detecting chlorine concentrations in water samples, chlorine concentration standards play a pivotal role. Standards such as **ASTM D1253** provide guidelines for testing chlorine demand, residual chlorine, and other related parameters in water. Adhering to these standards ensures that our testing methods are accurate, consistent, and reliable. By following established chlorine concentration standards, we can trust the results of our tests to provide meaningful data on chlorine levels in water samples, which is essential for ensuring water safety and compliance with regulatory requirements.

Furthermore, understanding and implementing chlorine concentration standards in our project ensures the accuracy of our testing methods. Incorporating these standards into our project design and execution demonstrates our commitment to achieving precise and reliable chlorine detection in water samples, ultimately contributing to the improvement of water quality and public health.

4.1.7 Android Application Standard

Adherence to Google's standards is crucial for developers that are aiming to publish their Android applications. These guidelines, which include visual experience, application performance, and security/data privacy, ensure that applications meet these firm standards before reaching users.

One of the application qualities is its visual experience, including navigation, notifications, UI elements, and graphical fidelity. Google emphasizes adherence to standard android visual patterns, using material design components for consistency across devices. This includes smooth navigation, support for back buttons and gesture navigation, restoring previous states after wake-up or

relaunch, and proper notification usage for ongoing events. Optimizing application performance is crucial for a smooth user experience. Key performance metrics include loading times, frame rates, SDK compatibility, and efficient battery usage. Google prioritizes zero crashes and ANRs (Android Not Responding), while also aiming for a consistent rendering rate of 60 frames per second to deliver a visually pleasing experience devoid of graphical glitches.

Privacy and security are one of the key components in the google guideline. Some of the criteria are such as minimal permission requests, contextual permission usage, clear explanations of permissions needs, and secure storage of sensitive data within the application to protect the user's privacy. Completing this comprehensive checklist serves as a guide for developers to evaluate their applications dimensions, stability, performance, user privacy. Including these guidelines will ensure the user satisfaction, the making of a high-quality application while meeting Google's standards.

How this pertains to our Project

Our senior design project focuses on developing a mobile application specifically for Android devices, with the intention of publishing it on Google Play Store. Including the Google specific standards is crucial for us, as it ensures not only the successful publication of our application but also a high quality user experience. Following these standards also plays a role in maintaining security of users' private information, helping to prevent any potential data breaches. Since our application provides real time updates, following the performance standard is essential for maintaining a consistent connection and preventing crashes.

4.1.8 iOS Application Standard

iOS standards are crucial for developers that are aiming to launch their application and provide users with a smooth experience. These guidelines include key areas to evaluate an application quality such as visual design, accessibility, functionality, performance, security, and Apple's App Store guidelines. iOS applications are expected to comply with Apple's Human Interface Guidelines (HIG) for a consistent and intuitive user experience. To meet the visual design standards, it is crucial that we adopt Apple's design principles and use UI Kit for creating user interfaces. This includes considerations for navigation patterns, screen layouts, typography, iconography and ensuring compatibility with multiple iOS devices and screen sizes. Also, the application should deliver accessibility to ensure inclusivity for users with diverse needs. The application must provide consistent functionality and high performance. This involves testing core functionalities, ensuring secure data handling, efficient implementation of background tasks, and smooth performance.

Security and privacy hold importance in iOS application development standards to safeguard user data. These standards include secure data storage, encryption protocol, user authentication, responsible permissions management, and

alignment with Apple’s privacy policies. It also involves tests to prevent data breaches. By incorporating this checklist into the testing and quality assurance, developers can guarantee the creation of a high-quality user-friendly iOS application.

How this pertains to our Project

Our future goal includes expanding our mobile application to include iOS devices alongside Android. To achieve this, we need to recognize the importance of familiarizing ourselves with iOS standards. This familiarity will enable us to make the necessary changes to our code and smoothly integrate Android and iOS functionalities, making it simple for future publication on the App Store. By including these standards across both platforms, we position our application for optimal performance, enhanced security, and a cohesive user interface, ensuring a smooth transition and a high quality experience for the users across different devices.

4.1.9 List of all Standards

Table 17. List of Standards

Section	Summary
Laser Power Standards	Ensuring laser safety is vital due to the sensitivity of the human eye to green light. We limit our laser power to below 5mW to prevent eye damage. Our system splits the laser, allowing power between 3mW to 9mW for safer use.
Software Testing Standards	Rigorous software testing protocols ensure the reliability and functionality of our system. Adherence to IEEE and ISO standards is essential for photodiode readings, water quality monitoring, and mobile app functionality.
PCB Standards	Adherence to IPC standards ensures consistent quality and functionality of PCBs throughout the production process. Design rules, file formats, soldering requirements, and inspection procedures are defined to guarantee robust and reliable electronic connections.
Hardware Communication Protocol Standards	Standardized protocols like USB or Bluetooth ensure reliable data exchange between components. Adhering to IEEE standards simplifies design and promotes interchangeability between devices, fostering flexibility and efficiency in the system.
3D Printing Standards	Y14.46-2022 standardizes 3D printing materials and techniques. Material extrusion and binder jetting are common methods. The standard allows flexibility while maintaining quality and performance standards.
Chlorine Concentration Standards	EPA Method 330.5 provides a guideline for measuring total residual chlorine (TRC) in water samples. Adhering to this method ensures accurate and reliable chlorine detection, supporting water safety and regulatory compliance.

Android Application Standard	Adherence to Google's standards ensures a high-quality user experience for Android applications. This includes visual design, application performance, and data privacy guidelines to guarantee user satisfaction and maintain security.
iOS Application Standard	iOS standards encompass visual design, accessibility, functionality, performance, and security. Compliance with Apple's Human Interface Guidelines (HIG) and privacy policies ensures a consistent, intuitive, and secure user experience across various Apple devices.

4.2 Constraints

Our project faces a range of constraints that pose challenges to its successful implementation. Economic constraints, such as our budget limit of \$1000, present a challenge in acquiring essential components such as laser sources and hardware. Meanwhile, environmental constraints underscore the need to carefully assess and mitigate potential ecological impacts, particularly in aquatic environments where laser activity occurs. Material selection, waste management, and compliance with environmental regulations further compound these concerns, highlighting the importance of integrating sustainable practices into our project. Ethical constraints, meanwhile, mandate strict adherence to safety protocols and ethical considerations to ensure the well-being of human subjects and minimize environmental harm. By considering these constraints and finding a way to work around them, we aim to develop a project that is economically feasible, environmentally responsible, and ethically sound.

4.2.1 Economic Constraints

In our project, the economic constraint of maintaining a total cost below \$1000 is a challenge, particularly in acquiring laser sources necessary for the chlorine measuring process. These laser sources, vital components of our system, are often priced in the thousands of dollars range, significantly surpassing our budget. Despite the variety of laser sources available in terms of wavelengths and power levels, finding one that aligns with our project requirements while remaining within budget has proven to be difficult. Moreover, the economic constraints extend beyond laser procurement; essential hardware components such as the microcontroller, sensors like GPS and photoresistors, and software hosting services also contribute to the overall project cost.

4.2.2 Environmental Constraints

We must consider various environmental constraints to ensure responsible and sustainable implementation. One significant consideration revolves around the potential ecological impacts of laser activity, particularly in aquatic environments

like pools. It's important to conduct thorough assessments to understand how laser use may affect aquatic ecosystems, including the well-being of aquatic organisms and overall biodiversity.

Material selection is also important to consider. By using environmentally friendly materials with minimal environmental impact, such as using 3D printing and using certain plastics such as PLA we can lower the environmental impact of our project. Waste generation is another concern, as laser operations may produce waste materials that require proper management to prevent environmental contamination. Compliance with environmental regulations is important, requiring adherence to laws governing water quality, waste management, and laser usage. Incorporating sustainable practices into the project's design and implementation, such as using environmentally friendly materials and optimizing energy efficiency, is crucial for minimizing environmental impact and promoting long-term sustainability.

4.2.3 Ethical Constraints

This project raises some ethical considerations that we need to address before diving in. While ensuring clean water is a beneficial goal, the methods we use need to be responsible and safe. The biggest concern is the laser light source. While it effectively measures chlorine levels, laser radiation can also be harmful to living organisms. If our system isn't properly designed, it could inadvertently expose aquatic life or even humans to unsafe levels of laser radiation. We'll need to prioritize safety by implementing features like enclosures, interlocks, or timers to strictly control when and how the laser is activated.

Another ethical consideration is the potential impact on the overall water chemistry. While we're targeting chlorine measurement, there's a chance the laser might also interact with other chemicals present in the water. This unintended consequence could potentially alter the water's overall composition in unforeseen ways. To ensure we're not creating a new problem while measuring chlorine, we'll need to research the potential side effects of laser interaction on the specific water source we're targeting. Transparency is also key. If our system introduces any minor changes to the water chemistry, we'll need to be upfront about them and ensure they fall within safe and acceptable parameters. By carefully considering these ethical constraints and prioritizing responsible design principles, we can develop a chlorine measurement system that delivers accurate results without compromising safety or introducing unintended consequences.

4.2.4 Sensor Constraints

The photodiode we've selected for chlorine detection is a solid starting point, but it's important to acknowledge some potential limitations that could impact the

project's effectiveness. One concern is its sensitivity. There's a possibility it might only be able to accurately detect chlorine within a narrow concentration range. If the actual chlorine levels in the water we're monitoring fluctuate more than that, we risk missing crucial readings. Calibrating the system for a specific range is an option, but that limits the overall flexibility of the design. A more promising approach might be to explore ways to amplify the signal strength from the photodiode, essentially making it more sensitive to the specific wavelengths of light associated with chlorine.

Another potential hurdle is the photodiode's selectivity. In an ideal scenario, it would only respond to light directly tied to chlorine presence. However, there's a chance it might also be sensitive to other chemicals or even stray light sources present in the water. This "crosstalk" from unwanted sources could lead to inaccurate readings and throw off our chlorine level measurements. To mitigate this, we'll need to investigate filtering techniques that can effectively block out these interfering signals. Alternatively, we could delve deeper into researching different chlorine detection methods altogether. Perhaps there are other sensor options that offer a higher degree of selectivity specific to chlorine, ensuring our readings are more accurate and reliable. By carefully considering these sensor limitations and exploring potential solutions, we can ensure our chlorine detection system functions effectively within the intended application.

4.2.5 Dimension Constraints

Since our project aims to be portable, staying within a compact size is crucial. The one-meter cubed dimensional constraint (1m x 1m x 1m) dictates our design choices. This translates to prioritizing miniature components like compact photodiodes and efficient control circuitry. Surface-mount technology (SMT) components are a great option due to their smaller footprint compared to traditional through-hole components. The enclosure itself needs to be optimized to comfortably house all the necessary parts without exceeding the volume limit.

Creative layouts and stacking strategies can maximize space utilization within the enclosure. If feasible, a modular design with separate, smaller enclosures for specific functionalities could be explored. This could not only improve portability but also potentially allow for easier deployment in various settings. Additionally, brainstorming collapsible or detachable features for specific parts, like collapsible legs for the enclosure or detachable sensor probes, could further enhance portability. Every bit of space matters. By meticulously evaluating component size and exploring miniaturization options, we can ensure an efficient design that adheres to the size constraint.

Focusing on a sleek and functional enclosure design that utilizes space effectively will be key. Online component databases with size filtering options can be valuable tools to find the most compact components. 3D printing the enclosure is an option

to allow for further customization and efficient use of space. Commercially available enclosures that fit within the size constraints and offer features like portability and weatherproofing are also worth considering. By carefully considering these factors and adopting a space-conscious design approach, we can ensure our project remains portable and readily deployable in various locations. Our team is actively utilizing Computer-Aided Design (CAD) software to establish a comprehensive digital model of our project. This model incorporates the precise dimensions of each hardware component such as the microcontroller, sensors, light sources, etc.

CAD allows for the evaluation of various layouts and configurations, enabling us to analyze how well each component integrates with the others. The organization and arrangement of hardware within the CAD model serves a critical purpose. First and foremost, it guarantees spatial compatibility within the designated one-meter cubed constraint. Secondly, it allows us to optimize the internal layout for optimal functionality. By leveraging the advanced capabilities of CAD software, we can proactively identify potential size conflicts early in the design phase. This proactive approach enables us to address any spatial challenges and refine the design for optimal functionality and a compact footprint.

4.2.6 Manufacturing Constraints

Navigating the manufacturability constraints for our Optical Chlorine Concentration Analyzer is a complex endeavor, shaped significantly by our project's budgetary limitations. As a college senior design project without sponsorship, these financial constraints impact every facet of our endeavor. From the outset, we must prioritize cost-effective solutions, especially given the need to source components from different manufacturers. Each component, be it laser diode, or sealant, must meet specific performance, compatibility, and availability criteria. These varying requirements can lead to delays in component sourcing and may necessitate design adjustments to accommodate available parts, potentially affecting project timelines.

Another key constraint is the use of 3D printing for multiple parts of our system. While this manufacturing method offers flexibility and rapid prototyping capabilities, it also presents challenges. The materials suitable for 3D printing might not always be the most robust or optimized for our application. Additionally, the layer-by-layer printing process can introduce structural weaknesses, raising concerns about the system's durability and longevity. Despite these limitations, 3D printing remains instrumental in our project, allowing us to iterate quickly and test different designs within our budget constraints.

Furthermore, the selection of materials for critical components, such as the sample chamber and housing unit, is pivotal for the system's performance and reliability. Balancing cost, performance, and availability becomes a significant challenge,

especially when considering materials' laser resistance, chemical resistance, and overall strength. Additionally, designing a user-friendly interface and ensuring ease of operation adds another layer of complexity to our project. While enhancing accessibility, this aspect increases the project's development time and necessitates thorough validation testing to ensure compliance with relevant industry standards and regulations.

Chapter 5 - Comparison of ChatGPT with other Similar Platforms

5.1 Generative AI

Generative AI stands as a forefront innovation in artificial intelligence (AI), showcasing machines' remarkable ability to produce new content closely resembling human-like patterns. These systems learn from extensive datasets to create text, images, or code that mimic human production. Notably, models like GPT (Generative Pre-trained Transformer) and GANs (Generative Adversarial Networks) have propelled generative AI into various domains, including natural language processing, computer vision, and creative arts. Generative AI models operate by discerning underlying patterns within the data they're trained on. Leveraging this understanding, they generate new content by predicting subsequent sequences or creating samples fitting within the learned data distribution. For instance, GPT generates coherent text based on user prompts, while GANs craft realistic images from random noise. While offering immense promise, generative AI also presents significant challenges.

Ethical concerns arise as these models can potentially produce misleading or harmful content without proper control or monitoring. Additionally, biases within training data may influence model outputs, requiring careful consideration. Despite these challenges, generative AI pushes the boundaries of AI research and applications. As researchers and developers work to address limitations and risks, it holds the potential to revolutionize industries, foster creativity, and enhance human capabilities.

5.1.1 ChatGPT

ChatGPT, developed by OpenAI, stands as a significant milestone in the evolution of natural language processing and conversational AI. Its ability to engage users in meaningful dialogues, provide assistance with queries, and even generate creative content has revolutionized the way we interact with AI-powered systems. ChatGPT has found applications in customer service chatbots, virtual assistants, and content generation tasks. However, its capabilities are not without limitations. Despite its impressive performance, ChatGPT may occasionally produce

nonsensical or irrelevant responses, especially in contexts requiring nuanced understanding or handling of ambiguity. Additionally, the model's susceptibility to biases present in its training data poses ethical concerns, as it may inadvertently perpetuate misinformation. Nevertheless, ChatGPT's intuitive interface and seamless integration across various platforms make it a valuable tool for facilitating communication and enhancing user experiences.

5.1.2 Google BARD Gemini

Gemini, like any complex AI tool, has limitations to consider. While the free tier offers strong language processing and access to Google Search for information retrieval, it currently only supports English and may not be available in all regions. Additionally, the most powerful version, Gemini Ultra, requires a paid subscription. Even with access to the latest information, Gemini's creative outputs, like code, might require human editing to ensure accuracy and polish. The ability to analyze information and provide relevant sources through Google Search makes it a valuable research assistant. Even with lower computational requirements compared to some competitors, Gemini delivers efficient performance. The current text-based version offers a glimpse into its future potential for handling diverse formats like visuals and code. However, there are areas for improvement. While Gemini can hold conversations, complex, nuanced back-and-forth exchanges that rely heavily on context might prove challenging. Additionally, getting the most out of Gemini can sometimes involve trial and error, requiring multiple attempts to achieve the desired outcome with specific tasks. Overall, Gemini is a versatile tool with immense potential. By acknowledging its limitations and capitalizing on its strengths, you can unlock its capabilities for various tasks, from research and information gathering to creative endeavors.

5.1.3 Microsoft Copilot

Microsoft Copilot represents a pioneering advancement in software development tools, leveraging AI to enhance coding efficiency and productivity. By analyzing code patterns and contextual information, Copilot provides developers with contextually relevant code suggestions, auto-completions, and even entire code snippets. Its ability to streamline coding processes and foster collaboration among developers can revolutionize software development workflows. However, Copilot is not immune to limitations and challenges. Despite its productivity benefits, the model may occasionally generate incorrect or suboptimal code suggestions, potentially leading to errors or inefficiencies in software development projects. Additionally, concerns arise regarding security vulnerabilities and biases present in the training data, highlighting the importance of rigorous validation and oversight. Nonetheless, Copilot's potential to accelerate software development cycles and empower developers with intelligent coding assistance remains promising.

5.1.4 Perplexity AI

Perplexity AI specializes in computer vision applications, offering robust capabilities for image recognition and interpretation. Its ability to accurately identify objects, scenes, and text within images has widespread applications across industries, including healthcare, manufacturing, and surveillance. Perplexity AI's efficiency and automation in processing visual information have the potential to streamline operations and unlock valuable insights from visual data. However, the platform is not without challenges. Ensuring accuracy and reliability across diverse environmental conditions and image types requires comprehensive training data and ongoing validation efforts. Additionally, biases inherent in AI algorithms may lead to skewed or inaccurate results, particularly for underrepresented or minority groups. Nonetheless, Perplexity AI's potential to drive innovation and efficiency in computer vision tasks underscores its significance in the field of artificial intelligence.

5.2 Comparison of AI

Table 18. AI Comparison

	ChatGPT	Gemini	Microsoft Copilot	Perplexity AI
Limitations	Limited code knowledge, data access cutoff date	Limited free tier functionality, outputs may require editing and human reviews	Limited conversation depth, subscription required for full access	Limited use per day, no human like conversation in engagements
Pros	Free tier available	Multiple answer drafts	Visual features	Ask prompts to be searched in specific categories such as Across all internet, Youtube, Wolfram Alpha, etc. Academic Accuracy

Cons	Not ideal for code-related tasks, outdated information and can be prone to misinformation, difficult math problems can't be answered	Limited conversation capabilities, trial and error for specific tasks	Requires developer environment and a subscription cost	Limited free use, limited conversation capabilities, does not integrate seamlessly with other apps/services
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5.3 Benefits to Senior Design

Incorporating AI tools like ChatGPT into the Senior Design process offers significant advantages, particularly in brainstorming and generating project ideas that cater to the diverse expertise of team members. With a team of two Computer Engineers and two Photonics majors, ChatGPT is a valuable resource for brainstorming sessions by facilitating collaborative exploration and the generation of relevant project concepts. One notable benefit of using ChatGPT in brainstorming sessions is its capacity to generate a wide array of creative ideas based on the input provided by team members. Through interactive dialogue, team members can pose questions or prompts related to potential project topics, exploring various areas of interest within the domains of computer engineering and photonics. For instance, inquiries could delve into emerging technologies, industry trends, or interdisciplinary intersections between computer engineering and photonics. Additionally, ChatGPT proves beneficial in explaining certain error codes or bugs in a manner that is easier to understand compared to some forums like StackOverflow. By inputting error messages or bug descriptions, team members can leverage ChatGPT to decipher complex technical issues and gain insights into potential solutions.

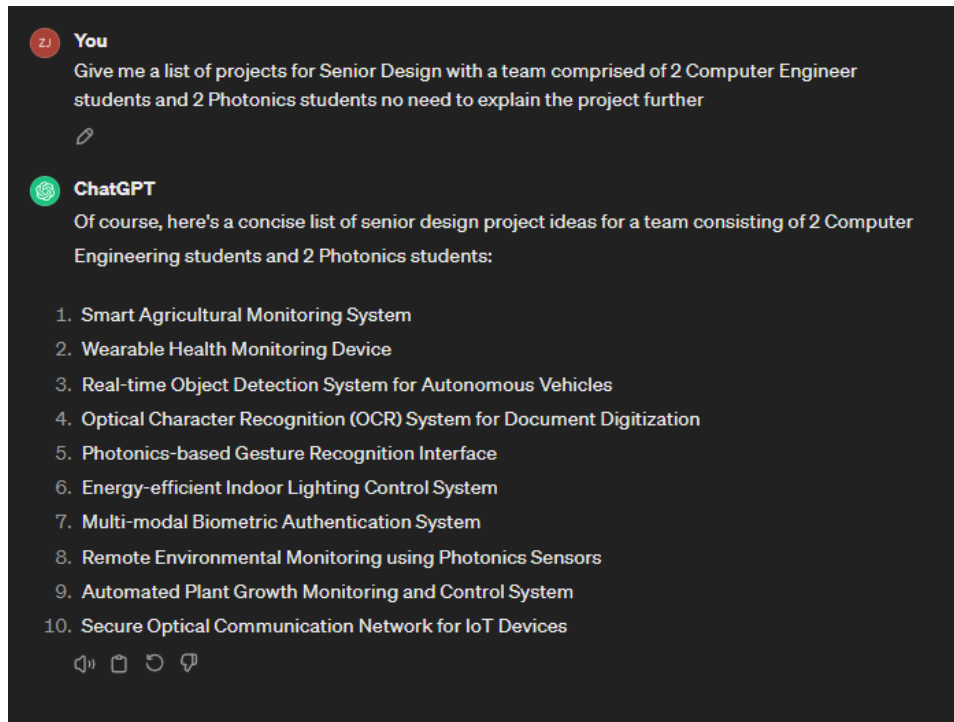


Figure 10a. ChatGPT user prompt & response.

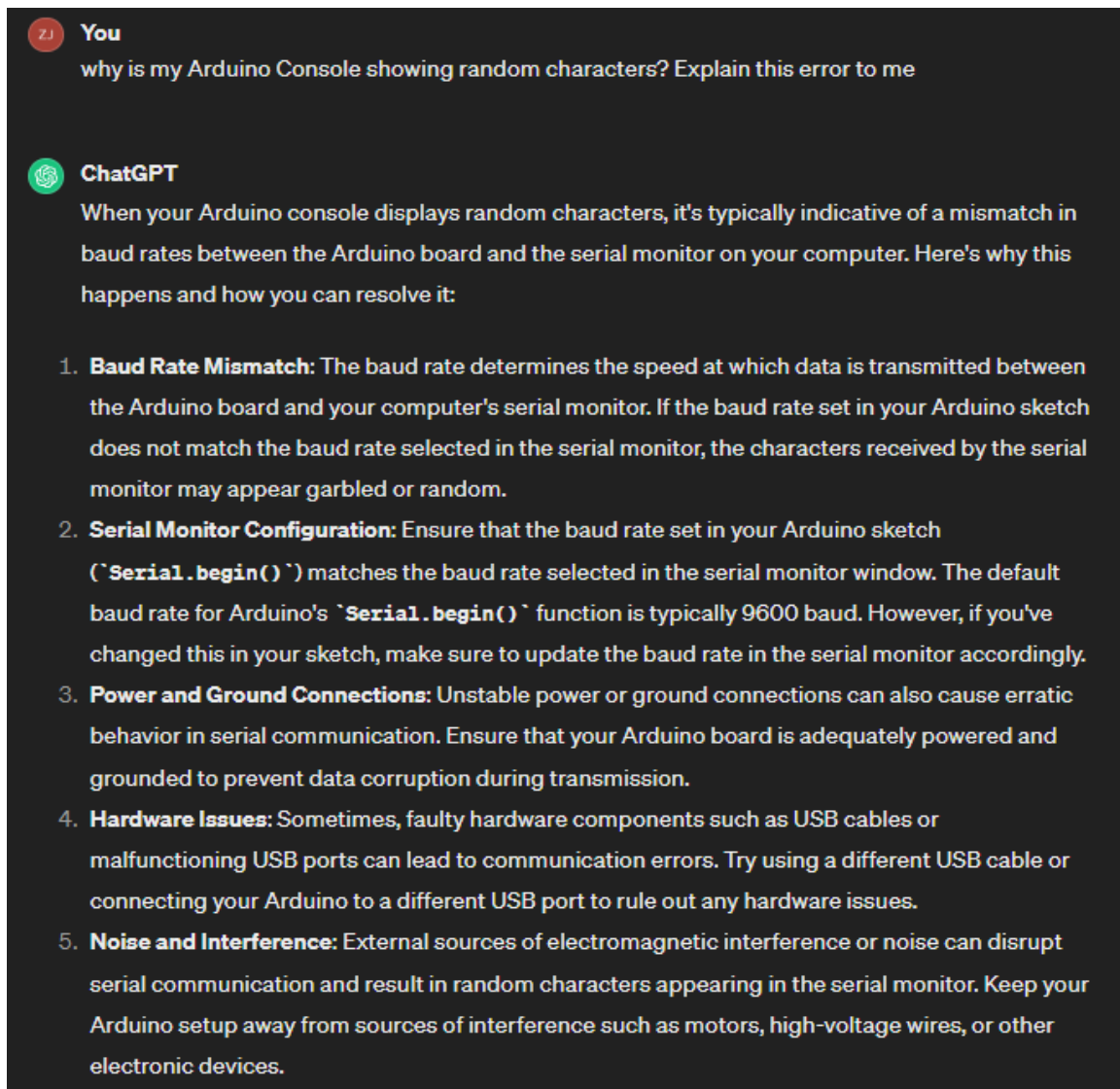


Figure 10b. ChatGPT user prompt & response.

5.4 Harms to Senior Design

Some challenges that may arise from using certain AI tools like ChatGPT is the reliance on resources that may not always be up to date. This limitation can impede the integration of new discoveries or emerging technologies into project designs. Given the rapid pace of advancements in various fields, including computer engineering and photonics, outdated resources may fail to capture the latest developments, leading to missed opportunities for innovation and optimization within Senior Design projects. In the context of coding and software development, the use of deprecated assets or outdated frameworks poses a considerable risk. Deprecated assets refer to elements within a coding environment or framework that have been marked as obsolete or no longer supported by developers. When these deprecated assets are inadvertently utilized in project development, it can

result in compatibility issues, decreased performance, and increased susceptibility to bugs or vulnerabilities. The consequence of relying on deprecated assets can cause project slowdowns, as time and resources are diverted towards identifying the cause of issues and implementing solutions. The use of deprecated assets may hinder the scalability and maintainability of Senior Design projects, as they may lack support for modern features or fail to align with current best practices in software development.

Chapter 6 – Hardware Design

6.1 – Optical Design

For our optical design, we need to denote explicit distances between all of our components to calculate the focal length we need to perfectly focus our system into the desired beam spot. The first constraint that can guide us is the house of quality from section 2.6, which states that our complete system can be no larger than 1x1x1 meters. This gives us plenty of room to work with, but we'd like to use far less space than a full meter, so instead we're limiting our optical design to be no more than 500mm in length across any given side, be it length, width, or height. The minimum estimated space we need to properly set up our system in between components is about 40mm, spoken directly from experience in the lab, so for our purposes we'll set distances to be no smaller than 50mm between each component to make alignment easier. Laser path 1 is the primary path we'll set distances for, with laser path 2 being dependent on the distances set for the first path as we'd like the length across both of them to be the exact same. With these constraints properly fleshed out and in mind, we've modified the optical layout from section 2.8 to have distances in between each component as well, to determine the maximum focal length our lenses can have.

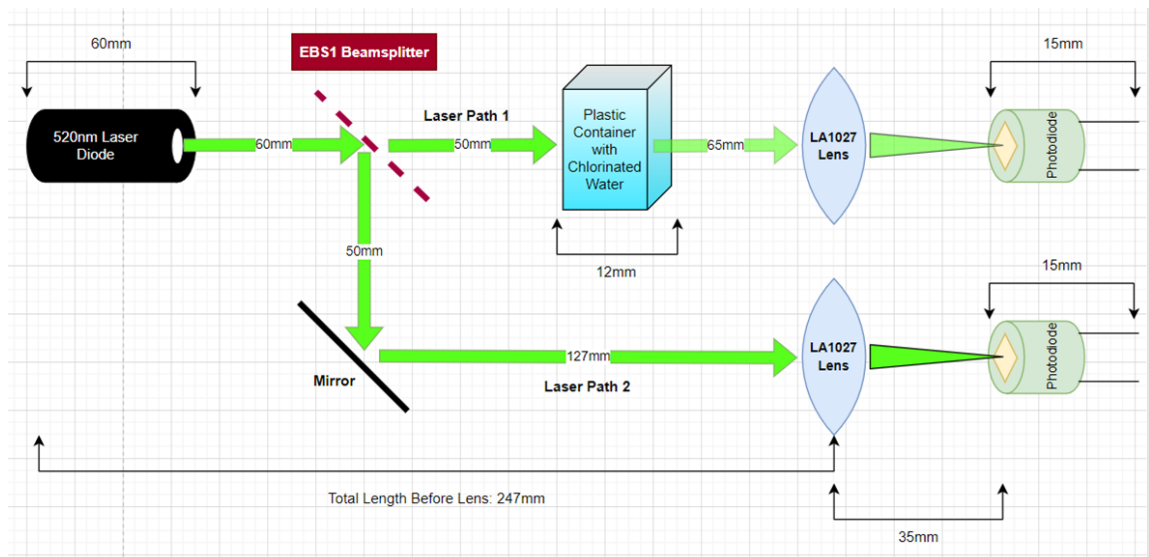


Figure 11. This is our layout with all our distances denoted, as well as the maximum distance we can have to the photodiode.

Now that we have the maximum distance from the selected lens of our system to the photodiode, we can use Zemax to model a variety of lenses and select one that doesn't have a focal length beyond the desired maximum distance while retaining a solid spot size at the photodiode. When setting up our Zemax parameters, we calculate our F/# by using the following formula:

$$F\# = (EFL/D_e)$$

Where EFL is the effective focal length of our selected lens and D_e is the diameter of our lens since it acts as our system's aperture stop. Additionally, we can set the distance after our lens to "variable" and set it to solve for the best spot possible, which we'll round to the first decimal since any measurements beyond that are difficult for human eyes to precisely set up. Once we set up the system in Zemax and take note of the result, we are seeking a lens which can give us the smallest spot size possible, which is considered perfect for our system once we find a lens that gives us diffraction-limited performance. Diffraction limited performance can be seen in Zemax by setting the spot diagram to show the airy disk. If the spot size is small enough to mostly fit in the airy disk, that is the best possible performance our system can achieve.

Using the aforementioned information, we tried about 12 Thorlabs lenses and 7 Newport lenses while attempting to solve for the smallest possible spot size. It was simply not possible to achieve diffraction-limited performance without changing the distance before the lens, but we found a lens from Newport that had amazing performance despite this, as seen in the following figure:

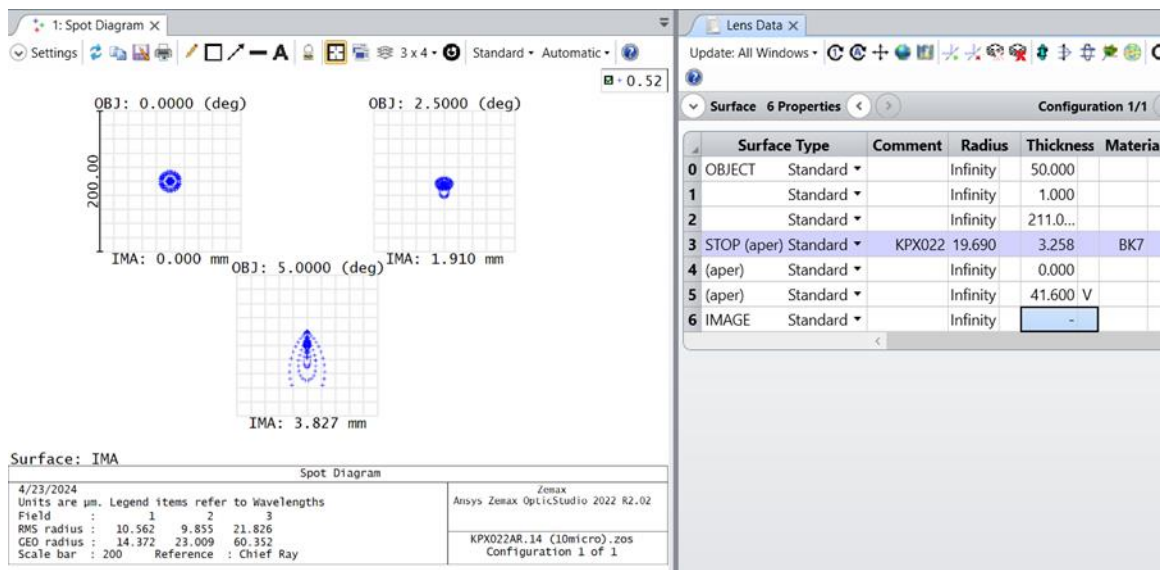


Figure 12. The smallest spot size across 19 separate lenses that we could attain. This performance belongs to the KPX022, specifically the AR coating which reduces the amount of loss through the lens.

Using Zemax's powerful ray tracing capabilities, a spot size of 10.5 micrometers was the smallest we could attain throughout our system. However, the Newport lens seen in the above figure is only 6.35mm in diameter, which makes it very difficult to focus in comparison to other options, which means that we need to compromise with the other lenses we compared. Amongst all of them, two stood out from Newport and Thorlabs due to their similarities in performance at 12.7mm diameter for both components: the KPX061AR.14 and the LA1027 respectively. Both of these components perform admirably at 30 micrometers spot size while on axis, which is still quite good for our system. Additionally, both come with Anti-Reflective coating which reduces the amount of power loss through the system, enabling the photodiodes to have an easier time detecting the signal. As far as selection goes, the Thorlabs LA1027 wins out due to its price being half that of the Newport KPX061AR.14, coming in at about \$21 to Newport's \$42. Thus, after much comparison and consistent use of Zemax, as well as multiple compromises, we arrive at the LA1027 lens being used for the detection portion of our system, with an effective focal length of 35mm.

6.2 – Schematic Diagram

Our schematic diagram, **Figure 18**, features an Arduino Uno Wi-Fi Rev 2, GPS Shield, two photodiodes, one laser diode, and one piezo speaker. The photodiodes are designed to read the laser wavelength when the laser is activated. The speaker emits a sound to alert the individuals of high ppm. Additionally, the GPS functionality displays the system's current location.

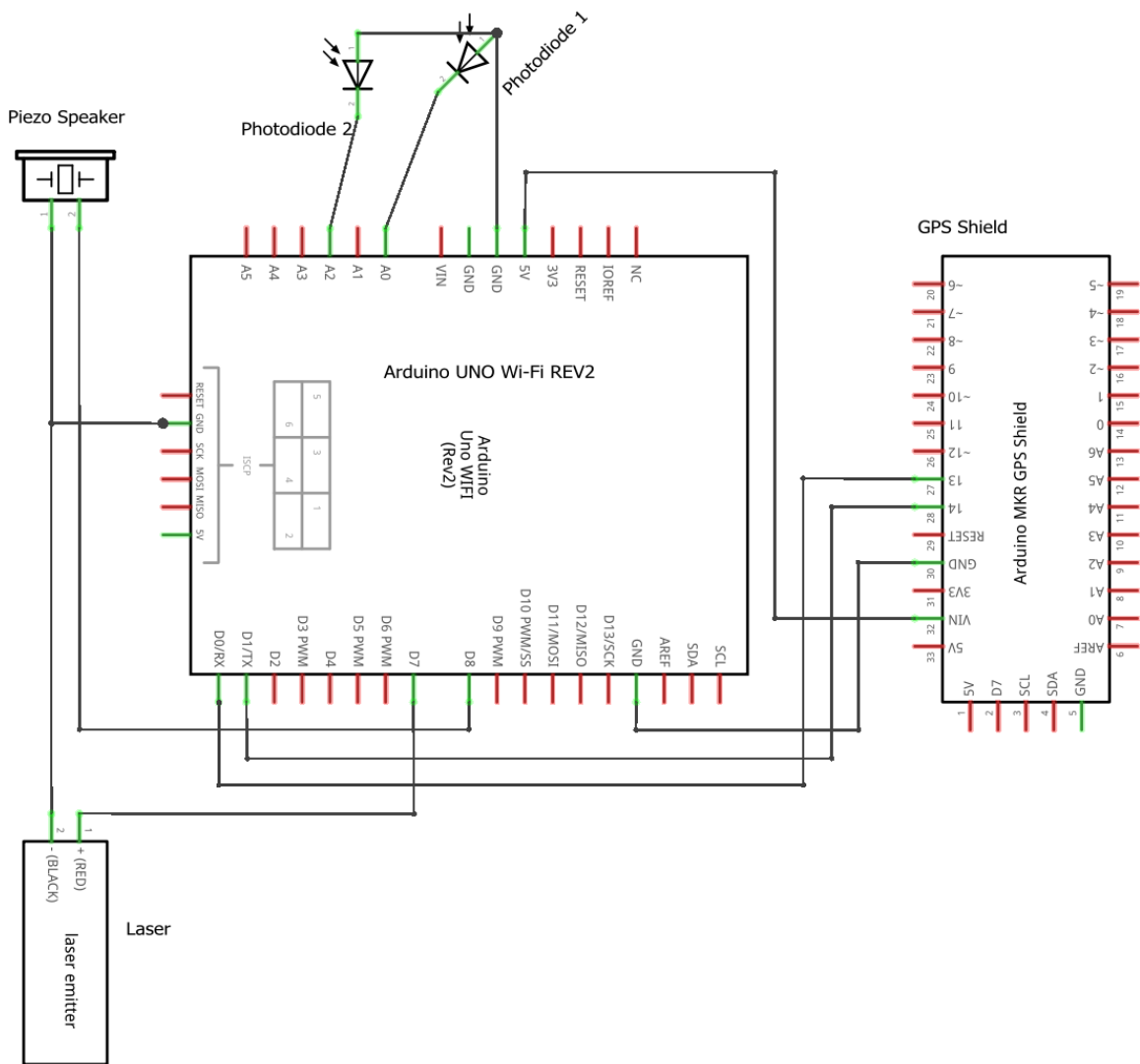


Figure 13. Schematic Diagram

Chapter 7 - Software Design

The project's software is divided into two main components. The first component is the mobile application, designed to provide a user-friendly interface for interacting with the chlorine concentration readings. Through the application, users can input commands and monitor the system real-time results. The second component is the embedded system, which serves as the bridge connecting the microcontroller and the mobile application. The microcontroller will be responsible for managing data communication, sensor inputs, and signals between the hardware and the mobile application interface.

7.1 Development Platform-Flutter

We chose Flutter for developing the mobile application due to its ability to create a single User Interface across different operating systems using a single codebase. This approach will allow us to reach a wider range of audience, as the application will be accessible on both Android and iOS platforms. Utilizing Flutter ensures a consistent user experience, as the application code remains the same across the operating systems. One of the advantages of using Flutter is simplifying maintenance and updates in the future. Since we only need to modify a single codebase, managing the application becomes significantly more efficient, leading to enhanced user satisfaction.

7.2 MERN Stack

Due to the complexity of implementing the backend in Flutter, we chose MERN stack to use the power of Node.js, Express.js, MongoDB for our mobile application's backend system, since React.js is used to make the Front end. One of the advantages of the MERN stack is dependence on a single programming language, JavaScript, throughout the development process.

7.3 Programming Languages

The front end of the Optical Chlorine Concentration Analyzer (OCCA) mobile application is developed using Flutter to create the User Interface with a set of widgets with the help of Dart programming language. On the other hand, the back end of the application is powered by JavaScript using the framework like Node.js, Express.js, and MongoDB to handle the server, data storage, and API. The combination of Flutter front end and JavaScript for the back end will provide an efficient development experience.

7.3.1 Dart

Dart is the primary language used in Flutter. Dart is a client-optimized language for developing fast apps on any platform. Its goal is to offer the most productive programming language for multi-platform development, paired with a flexible execution runtime platform for app frameworks. Dart shares similarities with Java, particularly in its support for object-oriented programming (OOP) concepts like classes, inheritance, and interfaces. This familiar OOP structure makes it easier to transfer to Dart. Also, Dart includes built-in support for asynchronous programming, allowing developers to write efficient code in handling tasks. By combining the

strengths of OOP with asynchronous programming, Dart has become a powerful tool for developing high-performance applications.

7.3.2 JavaScript

JavaScript is a high-level programming language most well known as the scripting language for Web pages. It enables dynamic and interactive features on websites by manipulating Document Object Model (DOM). JavaScript can run on both the client side, where it supplies objects to control a browser and its DOM, and the server side, where it provides objects relevant to running JavaScript on a server. This versatility makes JavaScript a great tool for full-stack web applications.

7.4 Gmail API

In our application, we will use the Gmail API to send notification to users regarding the chlorine concentration. When the process starts, it will send an email if the chlorine concentration exceeds 5 ppm and resend another email when the chlorine concentration returns to normal ppm. The integration with the Gmail API allows us to deliver timely updates directly to the user's email inbox with the information needed. In addition to these email notifications, the Gmail API will handle email verification for users. This verification process is crucial for users to access the email notification feature and also enables them to reset their password.

7.5 Mobile Application

When the mobile application is initially launched, it will guide the user through a login process where they will be prompted to enter their credentials. If the user does not already have an account, they will have the option to create one. This step is crucial for accessing the features of the Optical Chlorine Concentration Analyzer application. By logging in, the user's information can be securely retrieved from the database, enabling the application to display relevant OCCA results customized to their account.

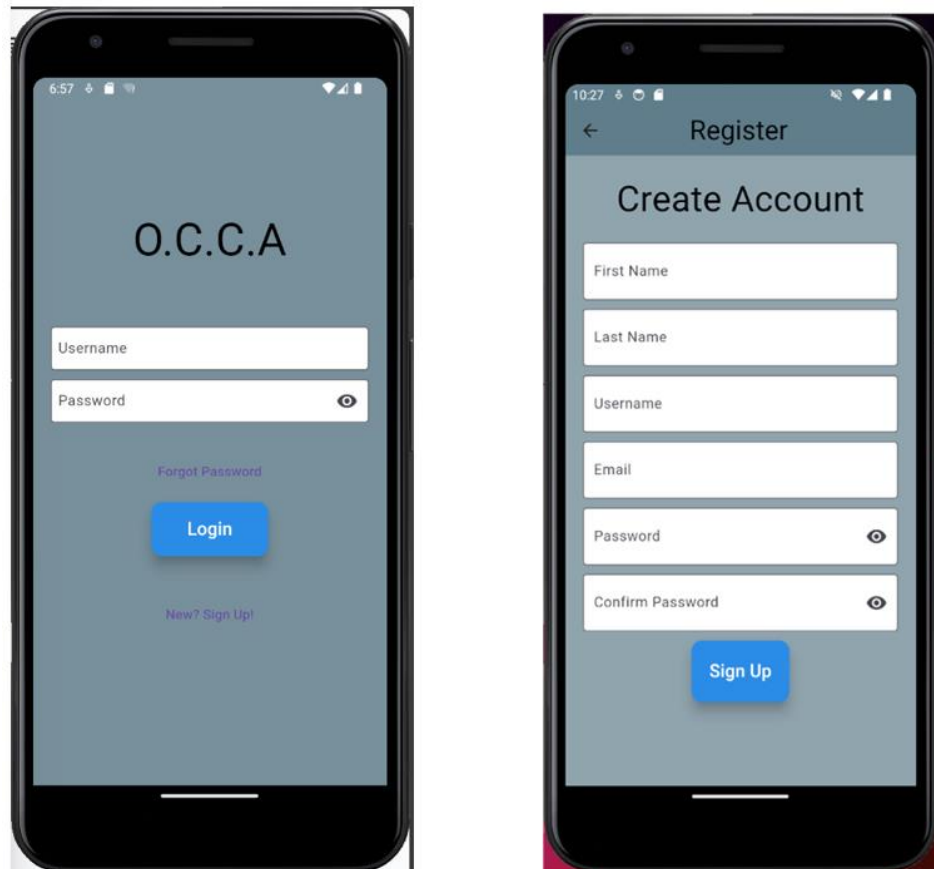


Figure 14. Login and Register for mobile application.

Upon successful login, the application will seamlessly transition the user to the dashboard page, where they will find a real-time display of the current chlorine concentration in the water. This concentration indicator employs a color-coded system, utilizing red, yellow, and green to visually represent different concentration levels. If the concentration exceeds 5 ppm, the display will be highlighted in red, signaling a high concentration. In the range of 2 ppm to 4.9ppm, the display will switch to yellow, indicating a moderate concentration. If the concentration falls below 2 ppm, the display will turn green, signaling a low concentration level. This color scheme allows users to quickly assess and understand the chlorine levels briefly, facilitating decision making regarding water treatment measures.

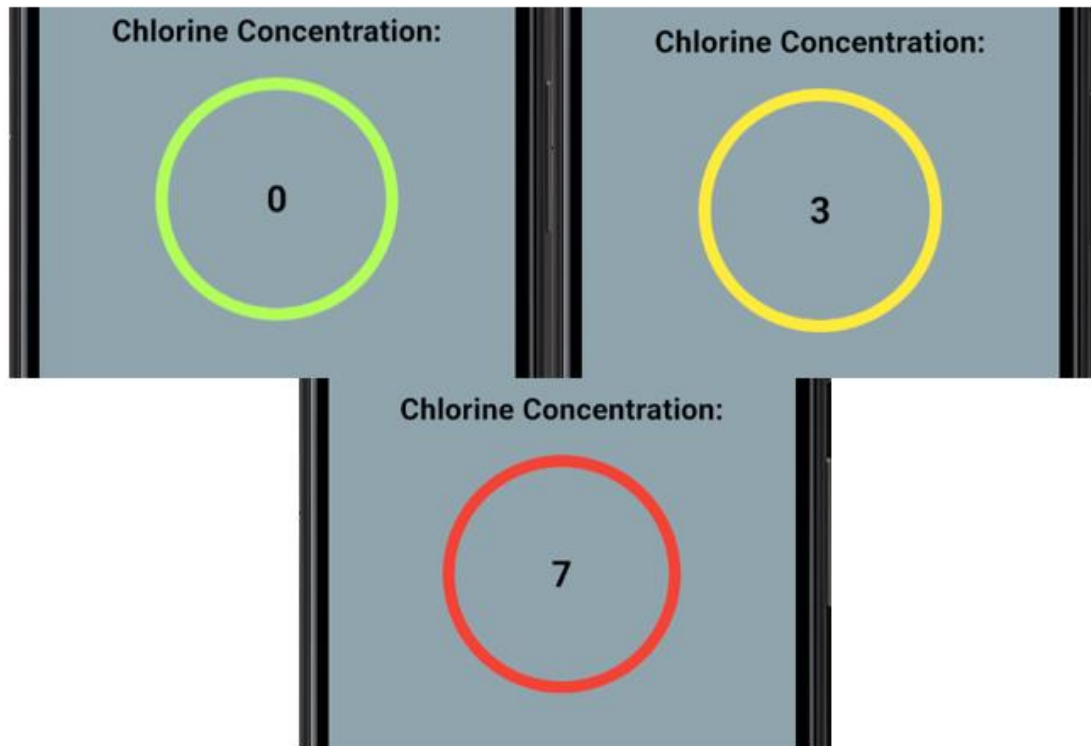


Figure 15. Display of Chlorine Concentration in PPM.

Upon pressing the start button, it will change the color to signify activation. As the process displays the concentration, users can stop it by pressing the start button again, effectively deactivating the reading process. When the process is active and the chlorine concentration exceeds 5 ppm, the application will send an email notification to the user. The email will include the date, time, location, and the ppm value. At the top of the dashboard, the current location of the system will be displayed. If the GPS signal is not fixed, a message indicating "No current GPS service" will be shown. This status will update in real-time as soon as the GPS signal is fixed.



Figure 16. Activate and deactivate reading process.

7.6 Mobile App Flowchart

Figure 4 illustrates the user journey within the mobile application, showcasing the navigation and control features embedded in the system. Upon launching the application, it begins in “start”, representing the beginning of the user interaction with the application. The next couple of steps are the paths the user can take to access the features, information, and interaction with the system.

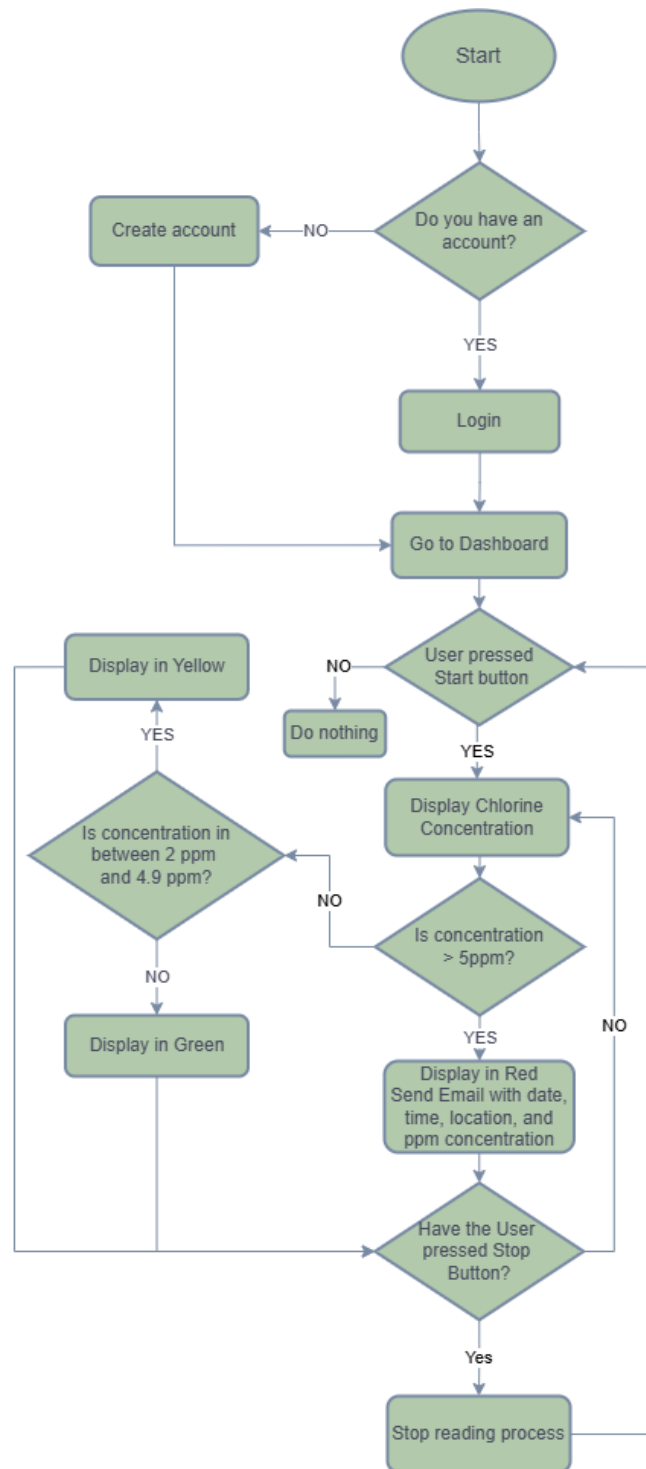


Figure 17. App Flowchart.

7.7 Use Case Diagram

SolidWorks is a powerful computer-aided design (CAD) software widely used in engineering and product design industries. It offers a comprehensive suite of tools for creating 3D models, assemblies, and drawings with precision and efficiency. With its user-friendly interface and parametric design capabilities, SolidWorks enables designers and engineers to visualize and refine their concepts before moving on to prototyping or manufacturing. Its simulation and analysis features further allow for testing design performance under various conditions, ensuring functionality and reliability.

In our senior design project, we utilized SolidWorks to CAD our housing unit for the chlorine concentration testing system. Leveraging SolidWorks' advanced modeling capabilities, we were able to develop detailed 3D models of the housing unit, incorporating all necessary components and ensuring proper fit and alignment. The software's parametric design tools allowed us to easily make modifications to the design, iterate on different versions, and optimize the housing unit for functionality and manufacturability. Additionally, SolidWorks' assembly features enabled us to visualize how each component interacts within the system, ensuring seamless integration and efficient assembly. Overall, SolidWorks played a crucial role in translating our design concepts into tangible 3D models, providing a solid foundation for the development and realization of our project.

The primary constraint that comes with Solidworks doesn't lie in the software itself, but rather the 3D printer that we use. The CREOL 3D printers have a 252mm x 252mm x 200mm printing area, which means we can't build the entire system and print it all out in one session. Instead, we need to build individual parts and fit them together, which means all designs must be made carefully to fulfill one section of each part of our project. To this end, figure 25 takes note of one of the most important sections of the project's housing, which is the foundation that will hold the chlorine sample, the laser diode, the beamsplitter, and the mirror. Should this foundation result in our optical system being misaligned, a lengthy 3D print will take up a great deal of time, which means the 3D model was made with consideration to all optical components, while simultaneously keeping the housing relatively small.

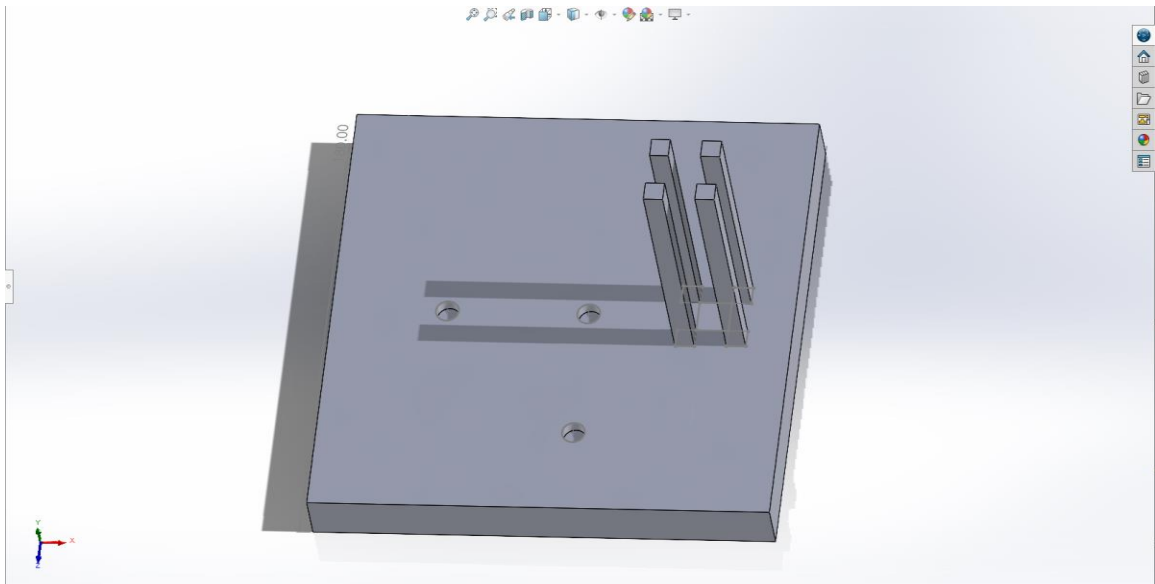


Figure 19. Primary foundation of the optical system. Total size: 180mm x 180mm x 120mm. Foundation is 20mm thick. 3 holes for the laser, beam splitter, and mirror, as well as 4 equidistant, 100mm-tall pillars small enough to secure our chlorine sample holder.

The next important section to 3D print was the rest of the foundation, which would hold the lenses and the photodiode PCBs. It would fit perfectly with the primary foundation and aligned with it as well, though Solidworks' assembly function made this much simpler than expected. Figure 26 shows the model in full, which is actually slightly smaller than the primary foundation to save some space.

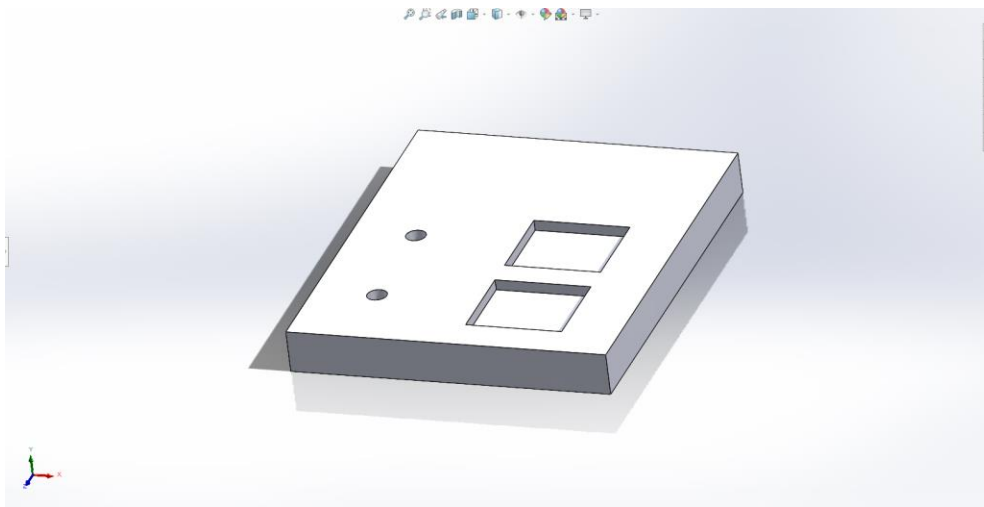


Figure 20. Secondary foundation. Total size: 180mm x 150mm x 20mm. 2 circular holes for our optical components and 2 rectangular holes for our photodiode PCB holders.

The purpose of the photodiode PCB holes was to ensure that we could print out the correct height that would fit the rest of the optical components. After 3D

printing the primary and secondary foundations and then putting them together using adhesive, we measured that the PCBs would need to be lifted by about 88mm to properly be aligned into the system, which led to the creation of the model seen in figure 27. Additionally, the distance between the PCB and the “cliff” of the model are specifically measured to accommodate for the filter, which is taped in front of our photodiode, to prevent oversaturation of photodiode voltage readings.

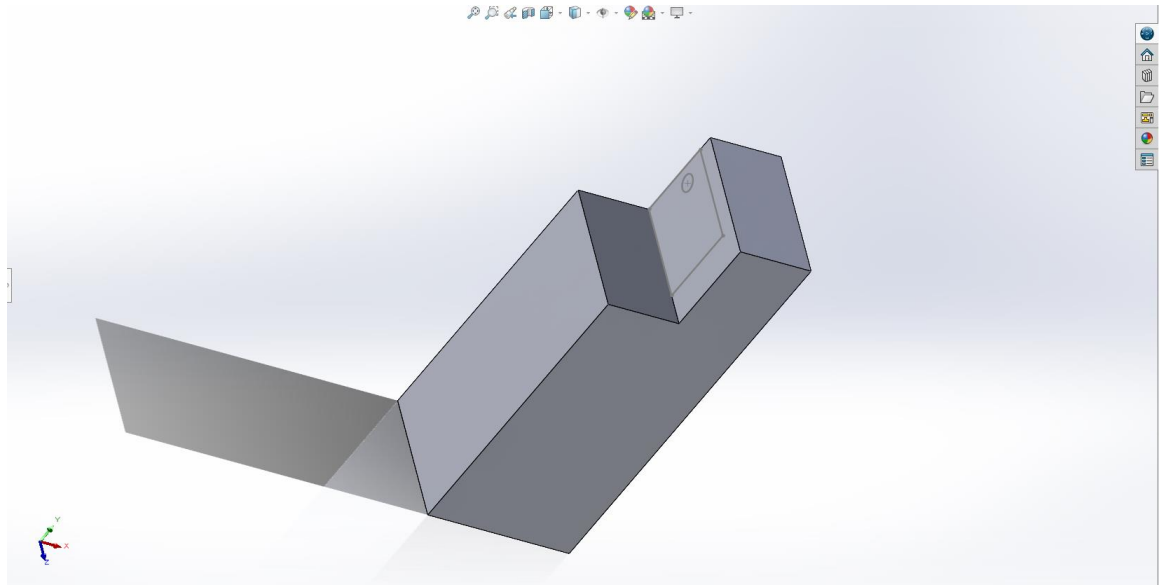


Figure 21. 3D model for photodiode PCBs. Total size: 39.75mm x 44.75mm x 128mm. Note the gray rectangle with the circular indent on the elevated surface. This denotes the way the PCB will be oriented and the location of the photodiode, which must be aligned with the rest of the system.

The 3D model in figure 27 fits well with the rectangular holes in figure 26. After 3D printing this section, we drilled holes into it and screwed our photodiode PCBs in, which held them well and at the correct height for our laser. After this, simple expansions were made to the primary and secondary foundations to hold our larger PCB, which powers the laser, photodiodes, and speaker. Then, the walls were made, usually 20mm or 10mm thick depending on the side, and assembled. These sections were not nearly as intensive to model and as such we won't show figures of them, although they did take multiple days to 3D print. Upon completion of the assembly of our project housing, which took exactly 2 kilograms of basic 3D printing filament, we then moved on to final calibrations of the system.

8.2 – Chlorine Sample Chamber

In our search for the optimal material for the sample chamber in our chlorine concentration analyzer project, we extensively evaluated various options to

ensure compatibility with our laser diode. We compared different plastics based on their laser diode compatibility, chemical resistance to chlorine, and cost-effectiveness.

Table 19. Chlorine Sample Chamber

Material	Laser Diode Compatibility	Chemical Resistance	Transparency
Acrylic	Mild transmission Efficiency	Good against mild chemicals	92%
Polycarbonate	High Transmission Efficiency	Excellent against chemicals	92%
Polypropylene	Low Transmission Efficiency	Excellent chemical resistance	50%
PTFE (Teflon)	Low Transmission Efficiency	Excellent chemical resistance	10%
PETG	Low Transmission Efficiency	Good chemical resistance	85%
PEEK	High Transmission Efficiency	Good chemical resistance	10%

Upon referencing the table above, we noted that either Acrylic or Polycarbonate would have the best performance for our system. The market offers a lot of choices for sample holders and they come in a variety of shapes and sizes. Our next consideration based on the information from table 21 and our research on the market led to us searching for a sample holder that can contain 10mL and is square shaped. 10mL is the sample size needed for our reagent to work best and the square shape makes alignment far easier as when light strikes a flat surface perpendicular to it, no refraction occurs. By taking advantage of this shape, we made alignment far easier for our system and simplified the process. In the end, we chose to use the LaMotte 0106 plastic test tube. Not only does this test tube fit the right shape and size, but its intended purpose is for use in water testing, which

means it can easily contain chlorine and DPD with no erosion to its structural integrity over a prolonged period of time.



Figure 22. LaMotte 0106 test tube. Square shape to prevent refraction. 10mL marked on the tube. Specifically created for water testing.

8.3 – Housing Adhesive

In our design, we plan to use a silicone-based adhesive to bond the housing parts to one another and ensure all our 3D printed sections are sturdy. Naturally, if the wrong adhesive is selected, we risk damaging our entire setup and possibly having to replace components. Some quick research suggested that a simple silicone-based adhesive would bond all our parts together easily, and as such we elected to use the M-1 sealant, as seen in figure 29.



Figure 23. *M-1 Sealant / Adhesive*

For our chlorine concentration analyzer project, we've opted for M-1 Sealant/Adhesive due to its remarkable combination of affordability and performance. This sealant is a UV-resistant, moisture-curing polyether that's solvent-free, making it environmentally friendly. Its aggressive bonding capabilities extend to various materials like EPDM, PVC, metals, and even glass. This versatility ensures a secure attachment of the UV LED to the sample chamber, essential for our application. Moreover, its underwater repair capabilities and high shear strength reinforce its durability, meeting our need for a long-lasting bond in a potentially moist environment.

M-1 Sealant/Adhesive stands out as an ideal choice for our project's bonding requirements. Its cost-effectiveness is paired with impressive features: UV resistance, moisture curing, and versatility in material compatibility. These attributes make it suitable for securely attaching the 3D printed sections to each other, ensuring a secure foundation which is crucial for our system's effectiveness. Additionally, its high shear strength of 380 lbs. per square inch ensures a robust bond, while its 290% elongation accommodates dimensional changes, including low temperatures down to minus 20 degrees F. The sealant's solvent-free composition aligns with environmental considerations, further enhancing its suitability for our project. In essence, M-1 Sealant/Adhesive offers a cost-effective and reliable solution that meets the precision, durability, and environmental requirements of our chlorine concentration analyzer.

8.4 – PCB Layout & Schematic

The printed circuit board (PCB) houses a photodiode, a 100nF capacitor, a 100k resistor, an LF351N operational amplifier, and four pin headers for powering the operational amplifier. These components work together to enhance the photodiode's performance as follows: the photodiode detects light intensity and converts it into an electrical current, 100K Resistor converts the current generated by the photodiode into a measurable voltage, LF351N operational amplifier amplifies the small voltage signal from the photodiode, making it strong enough for the Arduino to process accurately. It also maintains a linear relationship between the light intensity and the output voltage, 100nF Capacitor filters noise from the power supply, ensuring a stable and clean signal. Four pin headers provide the necessary power connections for the operational amplifier.

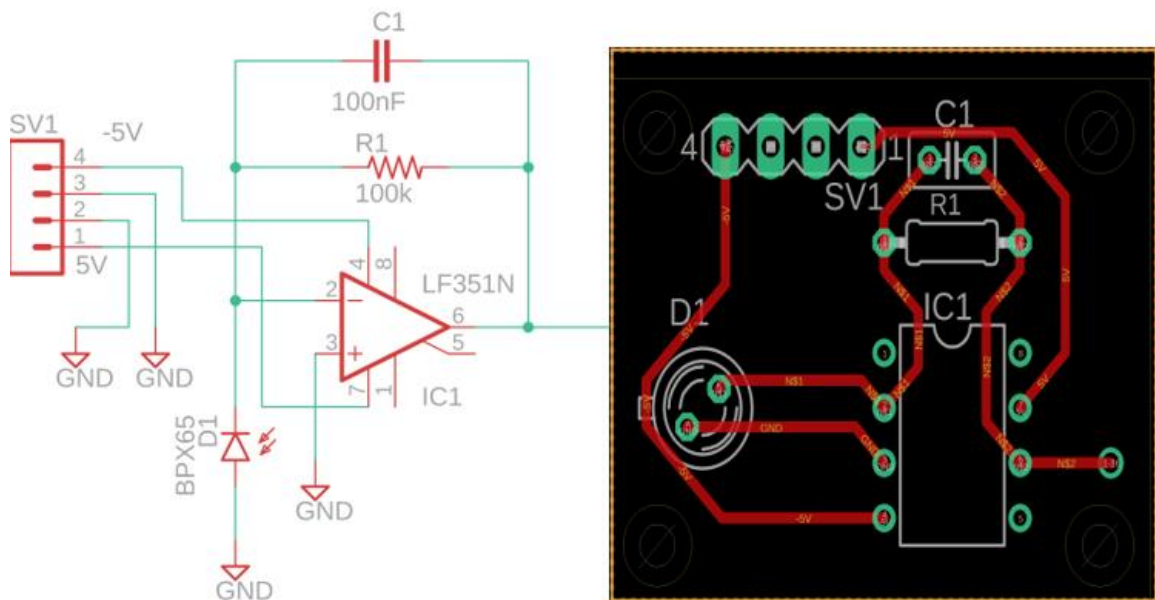


Figure 24. PCB Layout & Schematic

Chapter 9 - System Testing and Evaluation

9.1 – Hardware Testing

Our senior design project's hardware testing begins with an examination of the core components and their interaction with the central power source: an Arduino.

The initial phase prioritizes verifying the functionality of a laser and a photodiode. The photodiode plays a crucial role in monitoring the laser's power output by converting its light intensity into a voltage the Arduino can read. A push button simulates user interaction through a future mobile app and will also be integrated. The Arduino will act as the conductor interpreting the photodiode's voltage to track laser power in real-time. Additionally, we'll develop code to guarantee that pressing the button triggers a predefined action, mimicking user input from the envisioned app. Safety remains a top priority throughout testing. We'll adhere to strict safety protocols, including wearing proper eye protection when working with the laser. Following each test, we'll meticulously record and analyze the results, paying close attention to voltage readings, button press events, and any observations made during the process.

A successful Phase 1, demonstrated by properly functioning core components, paves the way for Phase 2. Phase 2 is the next stage and introduces a GPS module for location tracking and a passive piezo speaker to deliver safety warnings when there is laser and UV activity, further enhancing the project's functionality. This initial phase serves as a critical foundation, guaranteeing the core functionalities work seamlessly before we integrate the more advanced features planned for later stages.

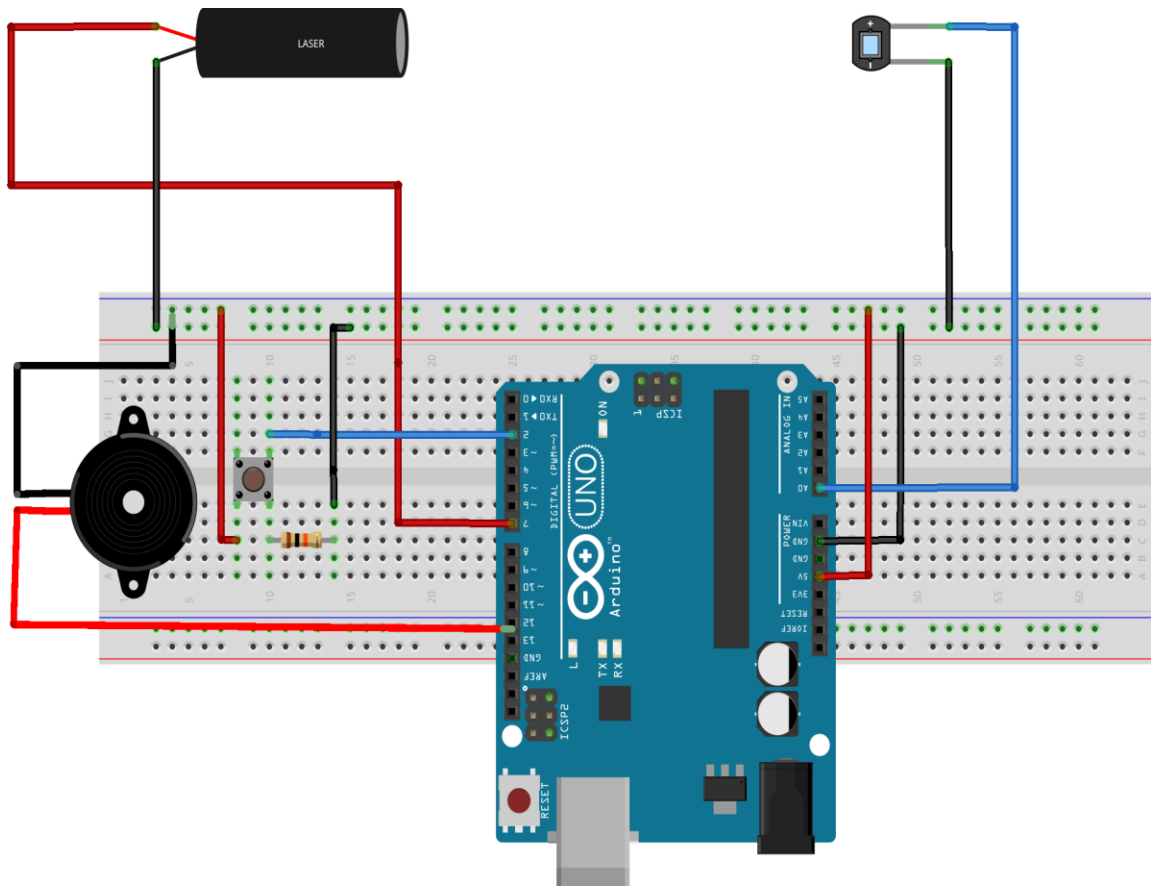


Figure 25. Configuration for Phase 1 Hardware Testing

Phase 1 of hardware testing began by ensuring each individual component worked. We tested the laser diode, photodiode, and speaker initially. We supplied power to the laser diode and ensured a collimated beam came out, then used some pre-existing code from the internet and ran it on the Arduino Integrated Development Environment (IDE from this point forward) to get readings from the photodiode. Without any light shined on the photodiode, we still get a relatively low reading, due to the location we were present at having illumination from the ceiling lights. Upon having our laser diode beam incident upon it, the reading on the photodiode increased by a reasonable amount, about 50% on average, though the reading was unstable since we tested this without mounting most of the components.

We then added some code which used the reading from the photodiode to determine when the speaker should begin making sound to alarm users of laser activity. Initial setup proved to be rather successful, as when shining the laser beam on the photodiode, the speaker alerted all nearby individuals by releasing a rather loud sound. Repeated trials had diminishing results however as our readings from the photodiode became more and more inconsistent, resulting in the speaker making noise even when outside of the desired conditions. We chalked this

inconsistency up to our system being unmounted and decided to restart the Arduino board, then add the button from Phase 1's figure, which would act as our app to control the laser diode. By adding some code to the Arduino IDE, we were able to turn the laser diode on and off by simply pressing it, and still retained the speaker response when the laser beam was shined upon the photodiode's sensitive area. However, the same issue arose from the previous trials as the photodiode became more inconsistent than ever, which demands that we run another set of tests with a more stable and fully mounted system to ensure this issue does not continue to plague our setup.

We noted that another potential cause of the issue could be from noise or interference from the button or other hardware components, whenever we pressed the button there was a spike in our readings from the photodiode and this caused our speaker to begin alarming us of potential UV/laser activity when the lasers were not on. Overall, phase 1 of hardware testing ensured that all our components individually performed as expected and made us aware of possible issues when integrating all our components together, which we'll keep in mind for the second phase of hardware testing. We are noting the fact that for our final product there will be less noise/interference because the button that was causing a spike in our readings will not be present because it will be replaced by the app sending UDP messages to our microcontroller.

9.1.1 - Laser Diode Beam Size

After the Apinex laser diode arrived, our first worry was ensuring that the beam wouldn't be problematic for our system. On the website that listed the specifications of the 520nm laser diode, there was no information about the beam itself besides it being a dot shape, so we used the setup from section 9.1's figure 6 and noted the width of the beam. It appears to be an elliptical beam spot, with approximately 4mmx5.5mm as the spot's length and width. This beam size is rather large for our purposes, and as such we do indeed need a lens to focus the beam down to a size that can fit within our photodiode to ensure a stable reading across both of them. Given that our photodiode has about 7.5mm² of radiant active area, which is approximately 2.74mm in a diamond shape, we'd need to ensure our beam can fit within that slim area to guarantee a consistent response. For this, we went to CREOL's Senior Design laboratory and used a lens with approximately 50mm effective focal length in our aforementioned configuration. This lens is simply a stand-in for testing and does not reflect the actual lens we'll be using within our system. We then aimed the beam at a non-reflective metallic ruler and took a picture of the beam spot size to get an accurate understanding of how large our spot size would be when focused, which is shown in figure 7.

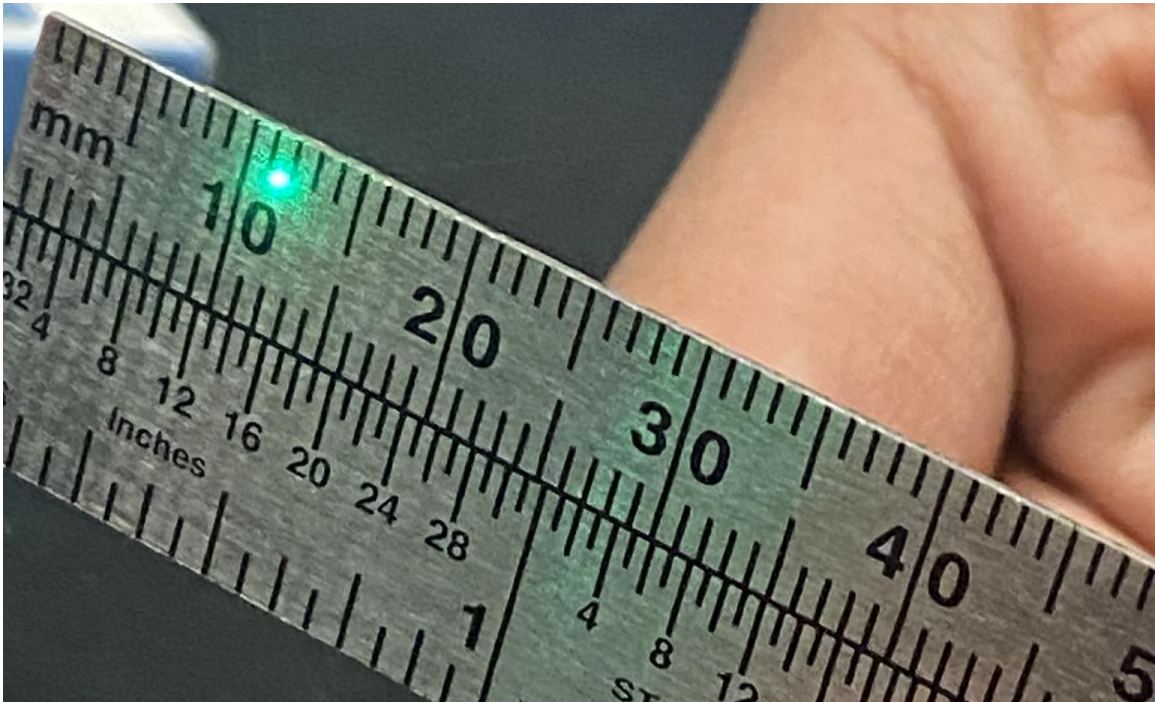


Figure 26. Focused beam spot size. Despite the elliptical parameters of the spot size, it focuses down to about 1mm in width and height at the focal point.

The 1mm spot size grants us plenty of room for movement when aligning our system to have the beam reach the photodiode's radiant active area, which takes care of one of the major concerns we had with this component. Selecting the correct lens is a matter of what we decide the distances between components should be in the optical setup and the coating of the lenses, if any, as any refraction can affect both alignment and power loss through the system.

9.1.2 - Photodiode Sensitivity Test

Next up in our testing was ensuring the BPW21R photodiode was properly reading our values. To accomplish this, we set up a simple circuit on a breadboard to power our photodiode and laser, then connected the arduino to it and shined the laser into our photodiode and read the values. We ran into a major issue here: the values read by the arduino would fluctuate heavily from maximum to minimum, oftentimes having an output similar to the following pattern: 0 to 83 to 897 to 1023 before dropping to 0 once again and repeating. These values were impossible to read regardless of alignment, so under the advice of a professor, we included a 100nF capacitor and 100k ohm resistor in our circuit. After this, we began to read much more consistent values, but had a noticeably weak signal. To remedy this, we added a LF351 JFET operational amplifier (op amp), which strengthened our read values greatly. The figure below shows our designed setup on the right, while the actual setup is present on the left.

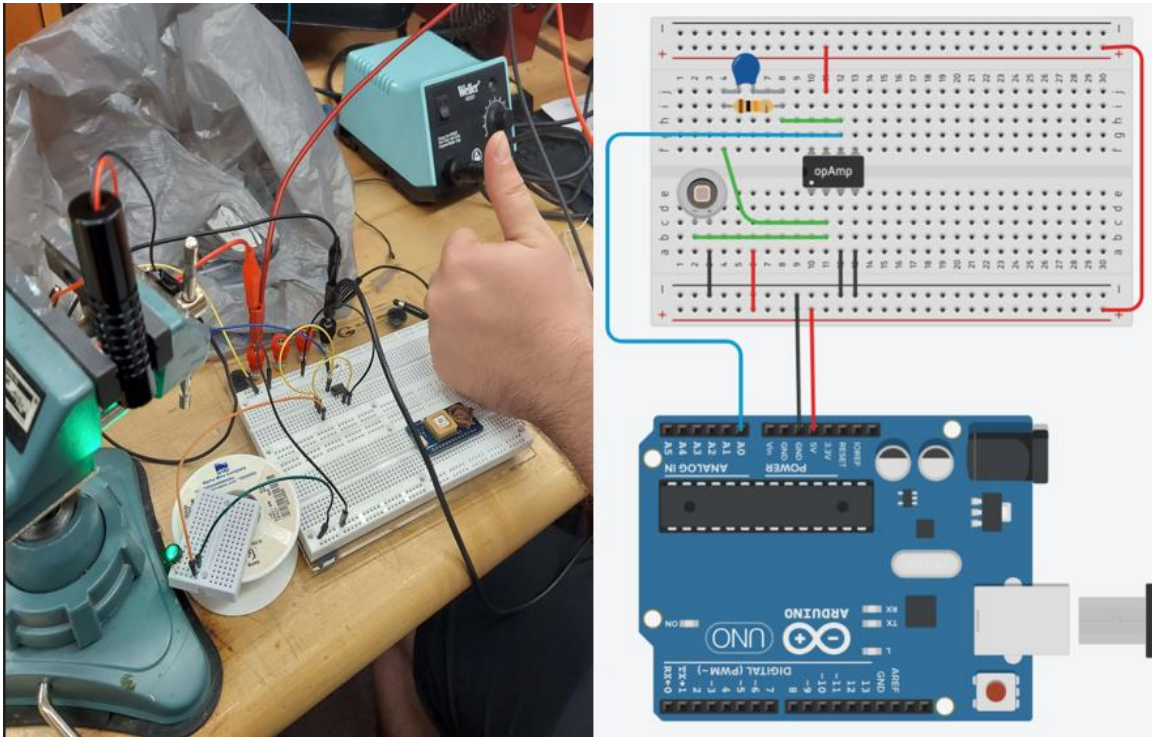


Figure 27. Photodiode testing setup. Left is an actual picture of the setup, right is the designed setup. Laser is perfectly aligned into the photodiode in the experimental setup and held tightly by machinery in the senior design lab, enabling good readings of our values.

With this setup, we read values across both tested photodiodes at about 900, which is 100 short of the maximum. With this in mind, we decided to reduce the optical power incident on the photodiode to make reading even easier by purchasing and integrating a light filter color correction film [69], reducing the read value across both photodiodes to about 575, which enabled us to finally have a starting point for our reagent testing.

9.1.3 - DPD Reagent Testing

Now that our experimental setup was complete, we began to test laser attenuation through DPD samples. For this, we gathered water from sinks at UCF and filled our test samples up to 10mL, then added a DPD packet into the sample and shook until the color settled. We then held the sample holder in the path of one of the photodiodes perpendicular to our laser to ensure little refraction and read the values. We read that at low chlorine levels, we'd see an attenuation between 250 to 300, or a reduction from 575 to about 275. At the time, we didn't take note of how much chlorine was within our samples. We then gathered water from pools and added DPD to them, producing much darker samples than the original tap water from UCF, which denotes a much higher concentration of chlorine present in the water. When added into the path in a similar manner, our photodiode read

between 50 to 90, which gave us proof that our method would work and only needed a solid housing to hold all components for calibration so we could begin reading chlorine concentrations in parts-per-million.

9.1.4 - Completed Optical Setup Testing and Calibration

After completing the testing from sections 9.1.1 to 9.1.3, we used Solidworks to model our housing and 3D printed all sections, then integrated our entire system into it. This section will take into account our calibration process as we converted our read photodiode voltage values into ppm values. Once the system was completely aligned and was reading consistent values, we began to create our own samples by taking purified water and adding low amounts of pool chlorine into them, then adding DPD to see the reaction. We used a chart, as seen in the figure below, to gain an idea of how much chlorine was present in the water sample we had taken. While it can be difficult to take note of what color falls under what category in the image, it is far easier to make a distinction in person. For this reason, we were confident in our ability to distinguish how much chlorine was present in any given sample by referring to the chart. We then prepared samples as close to the benchmarks in the chart as possible: 0.5 ppm, 1 ppm, 2 ppm, 3 ppm, and 5 ppm. We also prepared an additional sample which was darker than any seen on the chart. After preparing all these samples in water bottles, we poured them into our chlorine test tubes one by one and took note of the attenuation through the system in comparison to our base value, which was 420.



Figure 28. DPD chlorine ppm chart for system calibration. On the left is one of our samples, which is slightly darker than anything seen in this chart, putting it above 5 ppm. This was calibrated after we finished calibrating the rest of the chart.

By taking note of how much optical power was lost in the system and the values our arduino consistently read, we slowly calibrated our completely built system to be able to distinguish certain ranges based on loss from that data. We then began to test values that didn't fit into our chart, most notably ppm values far beyond the 5 ppm range, which were always darker than our chart's colors. The figure below is taken from our final demonstration, and is a more formal chart of what we did for our system's calibration to ensure our values were within our desired accuracy of 88% or above. For each value on the chlorine chart above, we did something similar, although we didn't save all of these calibration tests in excel spreadsheets since the process took some time to make consistent and we made our tests quicker by not having to document the entire process. Once we made our system consistent with values, our project was nearly complete. We interpreted certain photodiode voltage ranges into ppm values anyone could read and tweaked the threshold of our readings and speed of reported chlorine concentration into less spastic numbers. With all the hardware set in stone and the initial readings of our values, all that remained was the development of the mobile application, which promised GPS coordinates, a login system, an easy-to-use interface, and displays detected chlorine levels. Additionally, our application can remember multiple users and sends emails in real-time with all the aforementioned information in an email.

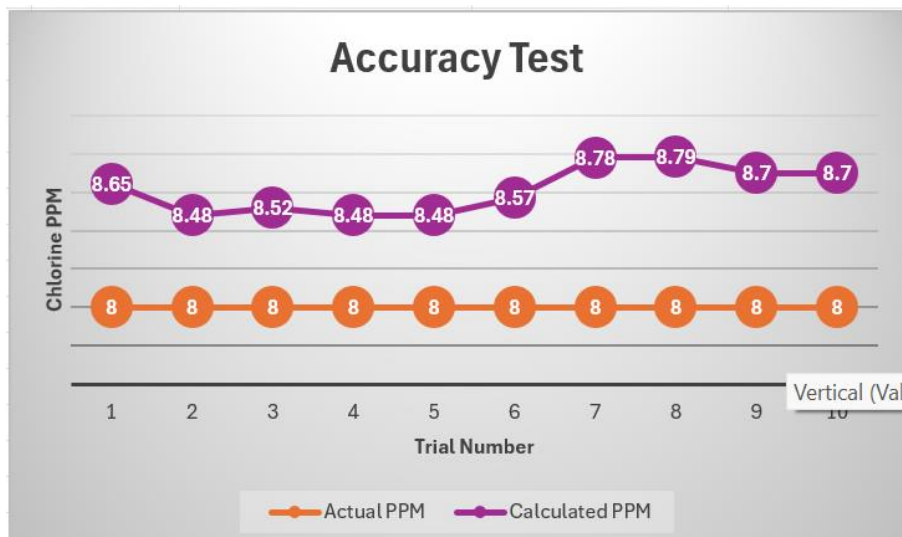


Figure 29. Accuracy test used in final demonstration. Our actual ppm was about 8, while our test was within +/-10% of that original value, giving us our 90% accuracy to call this project a success.

9.2 – Software Testing

Our software testing process for the mobile application begins by verifying the application's ability to retrieve information from the database. This will include establishing a reliable connection, fetching data efficiently, and accurately displaying it on the user's device. Additionally, we test the integration with the Gmail API to confirm that the application can send emails for notifications when specific actions are triggered. This ensures that the user receives timely updates and notifications based on the action needed. As we progress in our testing phases and the core components of the mobile application start working seamlessly with each other, we will move toward incorporating tests for the connection to the microcontroller. This will involve the communication between the mobile device and the microcontroller, as well as integrating data from the microprocessor into the mobile interface. This step is crucial for functionalities since it will rely on external hardware, ensuring that data is accurately captured and used within the application.

9.2.1 Postman

We will be using Postman to test the API of our project's software application. Our approach will involve defining a collection of API endpoints and requests within Postman. This collection will contain a range of scenarios necessary to our application functionality, such as data retrieval from the database, data updates, and the integration of email notifications using the Gmail API. The primary objective of this testing strategy is to confirm the accuracy of our software's API interactions. By testing the different endpoints and request types, we aim to identify potential issues, whether they involve data retrieval inconsistencies, update errors, or email notifications failures. Postman feedback includes returned data and error messages that serve as crucial indicators during the testing phase. One key for testing involves intentionally introducing incorrect or invalid data to evaluate how the code handles such scenarios. This practice ensures that our application remains stable and capable of handling unexpected inputs without crashing or returning invalid results. By simulating these cases, we can identify any vulnerabilities or weaknesses in our codebase and enhance the performance of our application.

9.2.2 Emulator

The emulator will show how the communication of the frontend and the backend components works together to make the user interface. The emulator will allow us to emulate user interactions, such as tapping buttons, entering text, and navigating through screens to ensure the frontend's behavior and responsiveness. Additionally, it can simulate any of the responses or data retrieved from the database using the backend component to display dynamic content in the frontend. The emulator's debugging tool will help us in identifying and resolving any issues

or inconsistencies between the frontend and backend, ensuring a smooth and reliable user experience upon deployment.

9.3 – Integration

To ensure a smooth integration process while minimizing debugging efforts we'll begin by conducting thorough testing of both the hardware and software independently. This involves verifying each hardware component, such as the laser and photodiode, with the Arduino, as well as testing the functionality of the mobile app in transmitting and receiving data using either UDP or TCP protocols. Once we confirm that each subsystem functions independently, we'll proceed to establish communication between the mobile app and the Arduino using the selected protocol. Ensuring reliable data transfer between these two components is critical for the success of our project.

To streamline the integration process, we'll adopt an incremental approach to adding hardware components. After the inclusion of each new component, we'll update the software to accommodate the functionalities of the newly added hardware component and conduct testing of the entire system, including both hardware and software, to ensure the interaction and data exchange works as intended. This incremental approach offers several advantages. It allows for early detection of bugs and simplifies the troubleshooting process by isolating issues to the most recently added component and its corresponding software update. Additionally, systematic testing at each stage ensures a strong foundation before introducing further complexity, thereby reducing overall testing time and bugs. Throughout the integration process, maintaining detailed documentation is crucial. This includes keeping records of schematics, code versions, and test results for future reference and troubleshooting purposes. Furthermore, implementing version control for our software code enables us to track changes and revert to earlier versions if necessary. Finally, we must carefully consider the trade-offs between UDP and TCP when selecting our communication protocol. While UDP offers faster transmission and is connectionless, TCP provides reliability and is connection-oriented. By following this phased integration strategy and conducting thorough testing at each step, we can effectively combine hardware and software components to create a robust and functional system.

9.4 – Performance Evaluation

The performance evaluation hinges on two crucial metrics: chlorine reading accuracy and mobile application capabilities. We prioritize achieving at least 88% accuracy in chlorine concentration readings; this level of accuracy ensures reliable data to send to the mobile application. Once our system's accuracy has reached its goal, we can develop the application further to interpret this data properly. To

evaluate these metrics, we will conduct chlorine reading accuracy tests, comparing our system's readings with standard laboratory analysis across various chlorine concentrations. Repeating this test with different initial chlorine concentrations will assess the system's performance across diverse scenarios. By analyzing these test results, we can evaluate the overall performance of our project and determine its effectiveness in achieving the desired chlorine detection and mobile application functionalities.

Chapter 10 – Administrative Content

10.1 – Project Budgeting and Financing

The funding for our group project budget is expected to be contributed to evenly by the members within the group. The anticipated budget for this project is \$1,000 to ensure the cost for each member is low. The budget is subject to change depending on the final hardware diagram (Specifically the gas detection section) and optimizing the system to achieve the parts per million or billion requirements. The budget includes a provision for replacement components that may arise throughout the project. Table 2 illustrates several key components necessary for initiating the development of an Optical Chlorine Concentration Analyzer.

Table 20. Budget

Component	Quantity	Unit Cost	Total
Laser Diode	1	\$40	\$40
Reagents	1	\$40	\$40
Arduino UNO Wi-Fi REV2	1	\$53.80	\$53.80
Piezo Speaker	1	\$7.99	\$7.99
GPS Module	1	\$40.10	\$40.10
Power Supply Adapter	1	\$7.99	\$7.99
Photodiode	2	\$10	\$20

Beam Splitter	1	\$38.32	\$38.32
Focusing Lens	2	\$25.81	\$51.62
PCB	5	\$3.00	\$15.00
Total			\$318.82

10.2 – Initial project Milestones

Our group was formed within the first week of senior design 1 and we are anticipating finishing senior design 2 in the summer. The team has planned milestones to keep us ahead of schedule due to having to finish the project in less time due to the shorter summer semester. The tentative schedules for senior design 1 and senior design 2 are shown in the tables below.

Table 21. Senior design 1 project Milestone

Task	Start Date	Anticipated End Date	Duration
Project Brainstorming	01/09/24	01/18/24	2 weeks
Divide and Conquer	01/18/24	02/02/24	2 weeks
Buy Parts	03/15/24	04/01/24	2 weeks
30 Page Milestone	2/2/24	2/23/24	3 weeks
60 Page Milestone	2/23/24	3/15/24	3 weeks
90 Page Milestone	3/15/24	3/29/24	2 weeks

120 Page Milestone	3/29/24	4/15/24	2 weeks
Individual System Testing	4/15/24	5/7/24	3 weeks
System Integration/Testing	5/7/24	5/28/24	3 weeks

Table 22. Senior design 2 project milestone

Task	Start Date	Anticipated End Date	Duration
Build Prototype	5/13/24	5/21/24	8 days
Test & Redesign	5/21/24	5/31/24	10 days
Finalize Prototype	5/31/24	6/20/24	20 days
Peer Presentation	5/31/24	6/5/24	5 days
Final Report	6/10/24	7/17/24	1 month
Final Presentation	6/10/24	7/17/24	1 month

Senior Design 2 Plan for Optical Chlorine Concentration Analyzer

1. Construction Phase:

- **Component Assembly:** Assemble the 3D-printed housing unit with the attached laser diode, lens system and sample chamber using M-1 Sealant/Adhesive.
- **Integration:** Incorporate the necessary electronic components for laser diode light emission and signal detection into the housing unit.
- **System Calibration:** Set up the system to initialize and operate as intended, ensuring all components are functioning correctly.

- **Build Prototype:** Create the prototype following our electronic schematic on a breadboard, ensure all the connections are correct before testing and calibration.
- **App Development:** Develop the frontend and backend of the mobile application and host the app making it downloadable through an Android SDK.

2. Testing and Calibration:

- **Initial Testing:** Conduct initial tests to evaluate the photodiode's effectiveness by shining our laser diode's light through the chlorine sample and taking note of optical loss through sample at varying concentrations.
- **Hardware Testing:** Test each individual hardware system to ensure each system is working as intended before integration.
- **Communication Testing:** Test the communication between the microcontroller and mobile application to ensure we can receive and transmit information at both ends.
- **Signal Acquisition:** Test the signal acquisition system to ensure reliable and consistent readings of chlorine concentrations.
- **Calibration:** Calibrate the system using standard chlorine solutions to establish a baseline for accurate readings. Adjust settings and parameters as needed to optimize signal clarity and accuracy.

3. Optimization Phase:

- **Parameter Adjustment:** Fine-tune parameters such as optical system alignment, signal detection sensitivity, and configuration of system based on test results.
- **Material Selection:** Evaluate the effectiveness of using different materials or sealants for the sample chamber to optimize performance.
- **System Efficiency:** Optimize the system's energy consumption and operational efficiency to ensure longevity and cost-effectiveness.

4. Trial and Error:

- **Iterative Testing:** Implement trial and error methods to identify potential challenges or issues and devise solutions to overcome them.
- **Feedback Loop:** Continuously gather data and feedback from testing phases to inform adjustments and refinements to the system.
- **Documentation:** Maintain detailed records of all tests, adjustments, and outcomes to track progress and facilitate informed decision-making.

5. Goal Achievement:

- **Chlorine Concentration Readings:** Work towards achieving accurate and reliable readings of chlorine concentrations in water samples.
- **Application Development:** Optimize the mobile application to receive, interpret and transmit information rapidly to achieve the desired response time.
- **Final Calibration:** Conduct final calibration tests to validate the system's performance and accuracy in measuring chlorine concentration in water samples.

6. Final Steps:

- **System Validation:** Validate the system's performance against project goals and requirements.
- **Documentation and Presentation:** Prepare comprehensive documentation of the design, construction, testing, and optimization phases. Create a final presentation summarizing the project's objectives, methods, results, and conclusions.
- **Project Review:** Conduct a project review to evaluate the success of achieving the project's goals, identify lessons learned, and discuss potential future improvements or applications.

Chapter 11 - Conclusion

To conclude our senior design project, we created an affordable system which can read chlorine concentration ppm values within 90% accuracy, complete with a mobile application which is easy to use. Additionally, the mobile application sends information about the location of the system, the detected ppm value, and whether or not this value is dangerous for human contact. Throughout the semester, our system underwent a lot of troubleshooting and consistently developed the project until it reached our final vision and fulfilled all our required engineering specifications. Throughout the last two semesters, we've learned a great deal about engineering as a whole and the methods one uses to solve complex problems, while developing our personal skills. At times, we had to learn about each other's fields to cohesively work together and occasionally learned new skills to be able to resolve problems as they arose. Overall, we believe our system is a success due to its solid performance when balanced against our final cost of \$318.82 and are thankful for this wonderful learning experience in the world of engineering.

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