July 15, 2020
Dr. Craig Scratchley
School of Engineering Science
Simon Fraser University
British Columbia, V5A 1S6

Subject: ENSC 405W/ENSC440 Design Specification for SpecTro

Dear Dr. Scratchley,
The team at photonicEyes has prepared a design specification document for SpecTro for ENSC 405W. We aim to create an air particle detector that can analyze the shape, size and concentration of the particulates in the air. SpecTro is an industrial product that will aid industries such as the forestry, medical and construction industries in detecting damaging particulates in the air.

The basic idea is to use a light source and arrange several silicon photomultiplier (SiPM) detectors in an experimented geometry to measure the light that is reflected or diffracted through the particles in the air. This design specification document discusses the technical details of the design requirements for each of the major subsystems of this device to meet the requirements of the proof-of-concept.

Our diligent team consists of 5 senior engineering students in the SFU program - Amirsaman Fazelipour, Kurtis Raymond, Raheem Mian, Ahnaf Tahmid and Sazia Tasnim. We plan to meet consistently and hold each other accountable for this project, and are confident we will produce an impressive product.

Our team would like to thank you in advance for taking the time to review our design specification. If you have any questions, please feel free to contact us through GitLab or email me at rmian@sfu.ca

Regards,

Raheem Mian
Chief Executive Officer
photonicEyes

Enclosure: Design Specification Report

Design Specification Document:

SpecTro

Team Members:

Raheem Mian: raheem_mian@sfu.ca (CEO/Researcher)

Kurtis Raymond: kurtis_raymond@sfu.ca (CTO/Researcher)

Ahnaf Tahmid: md_ahnaf_tahmid@sfu.ca (UI designer/Researcher)

Sazia Tasnim: sazia_tasnim@sfu.ca (Researcher)

Amirsaman Fazelipour: amir_saman_fazelipour@sfu.ca (Researcher)

Submitted To:

Dr. Craig Scratchley (ENSC 405W)

Dr. Andrew Rawicz (ENSC 440)

School of Engineering Science

Simon Fraser University

Contact Person:

Kurtis Raymond

Chief Technology Officer

kraymond@sfu.ca

778-255-1145

Issued date: 15 July 2020

Abstract

The goal of this document is to give the reader a detailed understanding of the design specification of project SpecTro by photonicEyes. The underlying principle as to the operation of SpecTro are explained, as well its intended purpose and its operation is shown. Details and processes leading to the creation of the design specification are discussed. This document will provide the reader with a justification for the design choices of SpecTro. The relevant engineering standards for the design specifications of SpecTro are also stated.

The detection system which will be explored is made from three main components:

1) Pulsed light system
2) Photon detector
3) Optical chamber

This document will focus on the technical details of SpecTro which comprises hardware, software, mechanical and operational components including an analysis into how our design choices are justified. This document will also include several sub-documents in the appendix that detail our final proof-of-concept test plan and our user interface. Our final proof-of-concept device will be presented and delivered by August 2020.

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Glossary

DAQ Data Acquisition System.

Impaction When small particles interfacing a bigger obstacle are not able to follow the curved streamlines of the flow due to their inertia, so they hit or impact the droplet.

OPC Optical Particle Counter.

PM Particulate Matter.

Quantum Efficiency The ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell.

SiPM Silicon Photomultiplier, an array of SPADS.

Size Factor A parameter which compares the wavelength of light to the diameter of a particle.

$$\alpha = \frac{\pi D_p}{\lambda}$$

SPAD Single Photon Avalanche Diodes, a high electric eld region promotes a cascade of electrons per signal on the sensitive region. Provides 106 gain.

UI User Interface.

UX User Experience.

1 Introduction

1.1 Background

This document aims to outline the technical design specifications for the air particle detector, namely SpecTro. These specifications are intended to describe the various design choices that were made in accordance to the functional requirements for the product, as outlined in the Requirements Specifications document for SpecTro [1]. The basic purpose of our project SpecTro is to detect air particulates in air and analyze them in terms of various properties such as shape, size, concentration, etc.

The foundations for this project are rooted in work done on a capstone by three undergraduate students at UBC, where they established the basic feasibility of the project. They constructed a basic proof of concept of a particle analyzer using a UV LED and three UV sensitive SiPM's at unique angles. The LED was pulsed, and measurements of the scattered light were recorded. However, the proof of concept ultimately failed to replicate the theoretical scattering curve of their 1.03um and 0.49um particle test sources [13]. A basic outline of the physics behind using light to measure the scattering is contained in the technical appendices. The main issues the team at UBC found with the system were associated with light leakage, dark noise, dark current, and other sources. Our plan is to analyze these problems and an appropriate solution through experimentation and simulation that can be feasible to the system. Investigation of potential solutions will include cost vs reward and reliability.

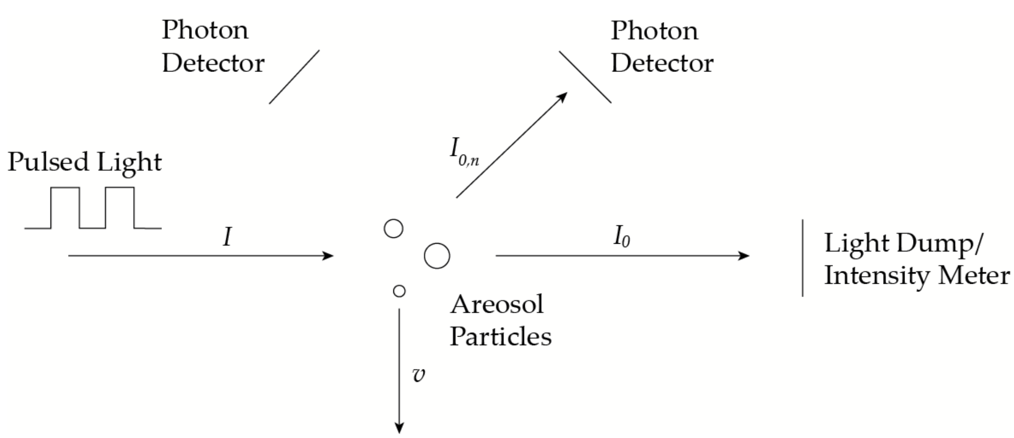


Figure 1: Basic principle of scattered light detector

Moreover, from the following relationship:

$$\alpha = \frac{\pi D_p}{\lambda}$$

where πD_p is the circumference of a particle and λ is the wavelength of incident light, we have 3 possible scenarios:

Rayleigh Scattering $\alpha << 1$: particle smaller than the wavelength of incident light
Mie Scattering $\alpha \approx 1$: particle almost the same size as the wavelength of incident light
Geometric Scattering $\alpha >> 1$: particle larger than the wavelength of incident light

This project will attempt to deal with the detection of particles much larger than the wavelength of the incident light using *geometric scattering*. However, we mainly wish to reliably measure the size of the smallest spherical particle using *Mie scattering* ($\alpha \approx 1$). The smaller the wavelength of our incident light, the smaller the particles that we could potentially detect.

1.2 Scope

This document outlines the design specifications for SpecTro which supports and seeks to satisfy the requirements specification document previously submitted. It traces the design choices and provides a justification for the designs we made for our project. This document also includes the Proof-of-Concept Test Plan in Appendix A and the User Interface Requirements in Appendix B. Note that a large portion of this product is still in the research phase, such as the measurement chamber, and largely depends on the results of ongoing simulations.

1.3 Intended Audience

This document serves the purpose of SpecTro's design requirements for photonicEyes Inc. This report is presented to our potential clients, Dr. Craig Scratchley, Dr. Andrew Rawicz and invaluable teaching assistants. Further research and data revisions will be provided from the specification layouts detailed in this document.

1.4 Design Classification

For the purposes of clarification and prioritization, the following convention will be used to label the design specifications throughout this document:

Des {Section}.{Subsection}.{Specification Number} {Stage of Development}

The design requirements are organized within the main sections of the document. The subsection corresponds to subsystems of the product. Individual requirements are labeled according to what stage they are to be achieved.

Label	Stage	Description
Dev X.X.X P	Proof of Concept	Requirements to be met at the end of ENSC 405W
Dev X.X.X E	Engineering Prototype	Requirements to be met at the end of ENSC 440
Dev X.X.X F	Finish Product	Finished to market product

Table 1: Development stage encoding

1.5 System Overview

SpecTro consists of three main components: Pulsed Light System, Photon Detector and the Optical Chamber. The detailed specifications for each system will be outlined in their corresponding sections throughout the document, whereas a general diagram of system overview of the main components is posted in Figure 2 and our specification requirements are organized in a cloud diagram in Figure 3. Since our project is largely based on this cloud diagram, we thought it was prudent to include it here. Additional details are provided later in this document which explores the different sections of the cloud diagram.

Figure 2: System overview of main components

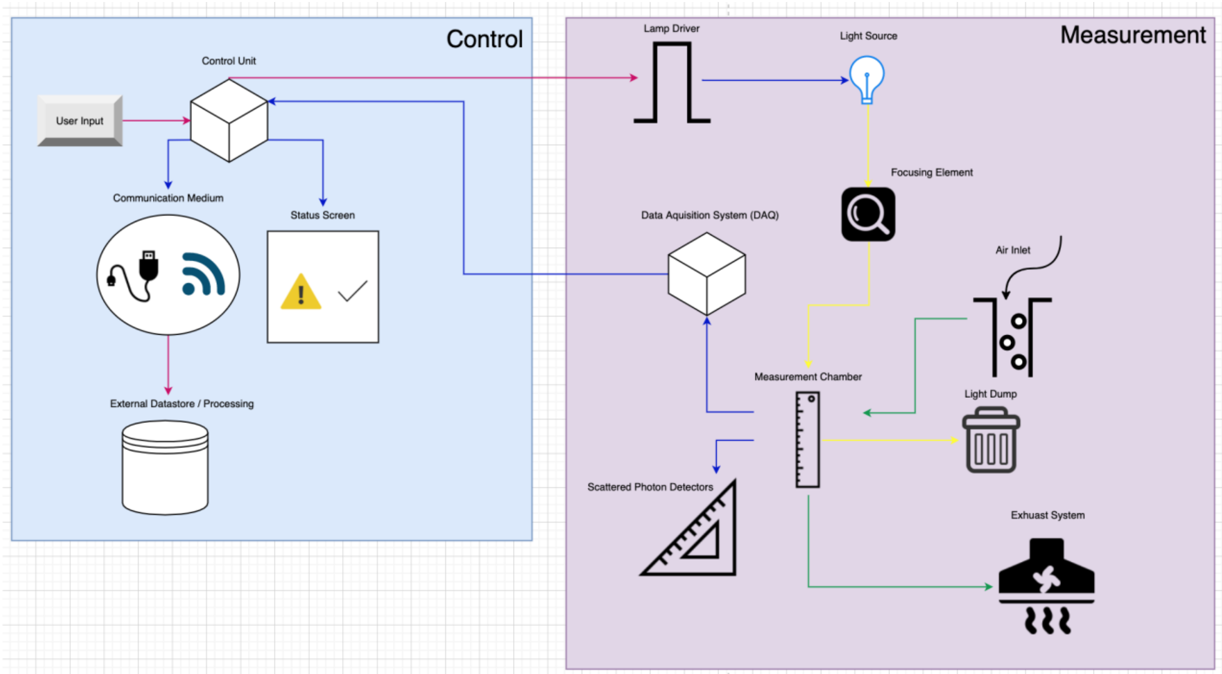


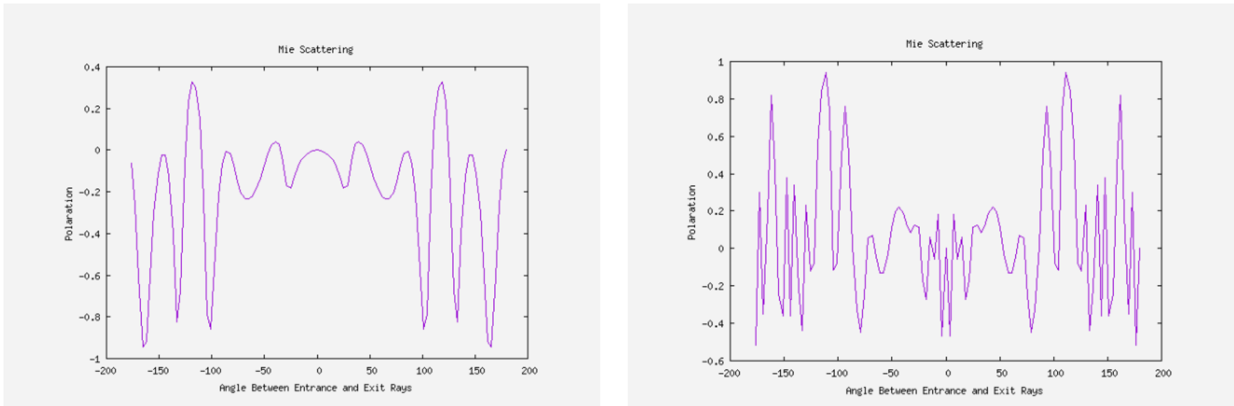
Figure 3: System overview of sub-components [1]

2 General Requirements

This information relates to the project as a whole, and not necessarily one part. We discuss some of the theoretical underpinnings.

2.1 Light Scattering Simulations

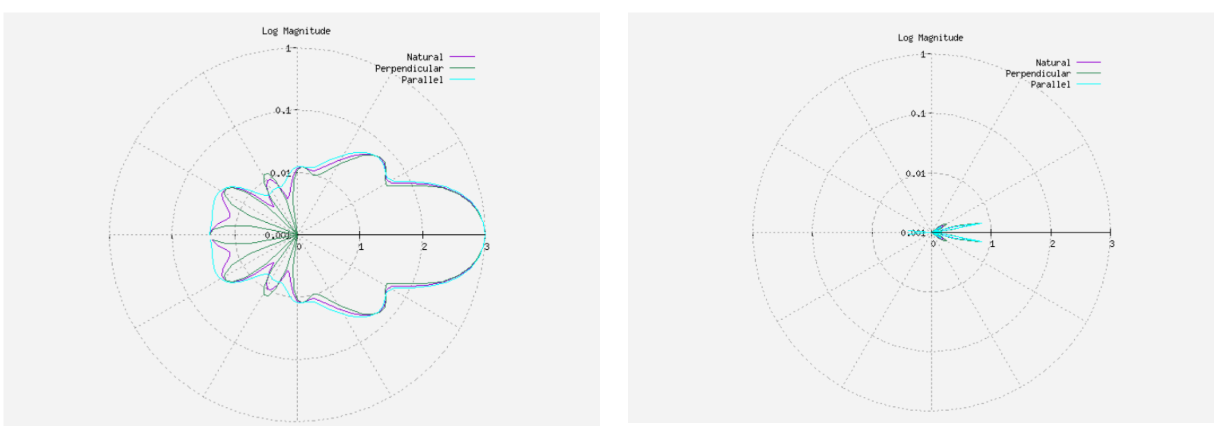
An important consideration is the placement of detectors (sensors that detect particulate in the air) and having the optimal number of detectors. We are able to simulate light scattering off of different shaped particulates and this will aid us in solving this problem. Although we can simulate ideal situations, the best results will be seen through experimentation. There are many tools that can be used for simulations. One is a mie scattering calculator online that is only used for sphere shaped particles[18]. Figure 4 shows the oscillation of the incident beam over a wide range of angles. As we move the detector closer to the particulate the frequency of the oscillation increases. What we want from our design is for the detector to be at a position to have median oscillations. We can simulate this by increasing the radius of the particulate, but this step will yield better results in experimentation.



(a) (b)

Figure 4: Polarization vs Angle. Radius : (a) 1 microns. (b) 0.1 microns. [18]

Another design consideration is the placement of the detectors. Figure 5 illustrates the scattering off a spherical particulate where the incident beam is flashed towards the center (location of the particulate). A lot of scattering is shown to be at 0 degrees and +/- 45 degrees for microns sized 1 - 10 microns. Optimal location for the detectors then would be towards the center +- (45/2) and 0 degrees. Initial assumptions are that 3 detectors would be adequate for the system, through experimentation can this assumption be validated.



(a) (b)

Figure 5: Polar graph of radial distance (log scale). Particle sizes: (a) 1 micron, (b) 10 microns.[18]

Figure 6 illustrates the scattering angles for cylindrical particles and assumes symmetry. It shows that it peaks at 0 degrees and diminishes as the angle furthers from 0 degrees. I believe the initial assumption detailed above for spherical particles can also be assumed for cylindrical particles [10,11,12].

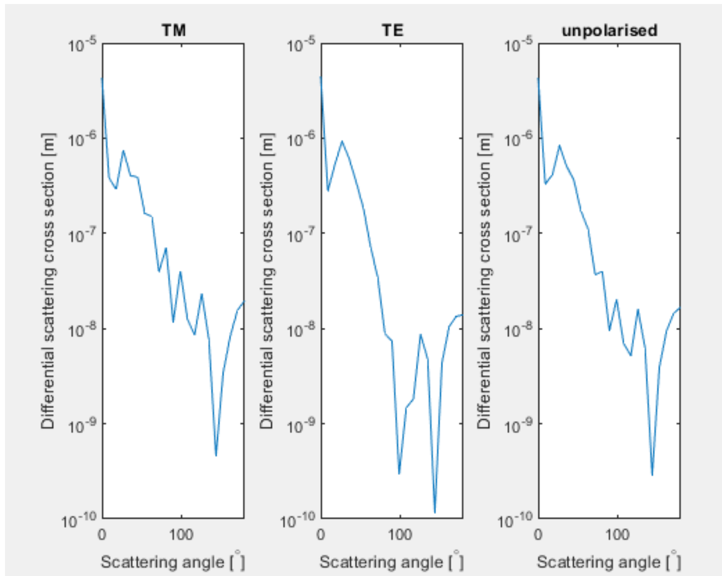


Figure 6: Scattering angles for a cylindrical shaped particulate with diameter 2.0525 microns [10,11,12]

3 Measurement

These sections correspond to those systems on the right hand side of Figure 3.

3.1 Air Inlet

Dev 3.1.1 P	Air should be accepted through the inlet excluding light
Dev 3.1.2 P	Prevent impaction of particles between 0.1 microns - 100 microns
Dev 3.1.3 P	The exit angle into the measurement chamber should be kept small
Dev 3.1.4 P	There should be minimal mixing of sample air and cleaned air
Dev 3.1.5 P	Needs to be removable to allow for other types of inlets/accessories

Table 2: Air inlet design specifications

The air inlet is required to let air in, but no light. It must also be configured to not cause impaction of particles between 0.1um to 100um particles.

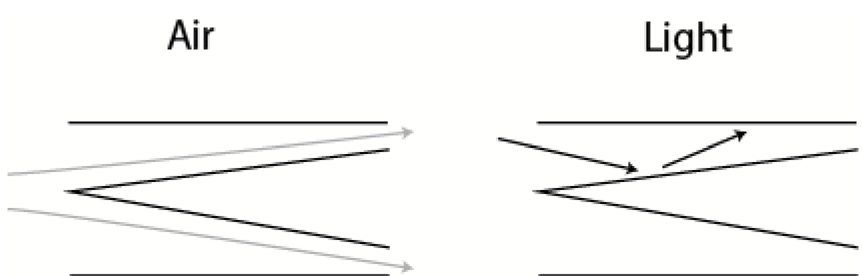


Figure 7: Air inlet geometry example

In the above image, a potential inlet geometry is shown. Note that air and light travel different paths, and if the surfaces are coated with some carbon black type material, the light will be effectively extinguished after a couple bounces. Another potential inlet geometry is shown below.

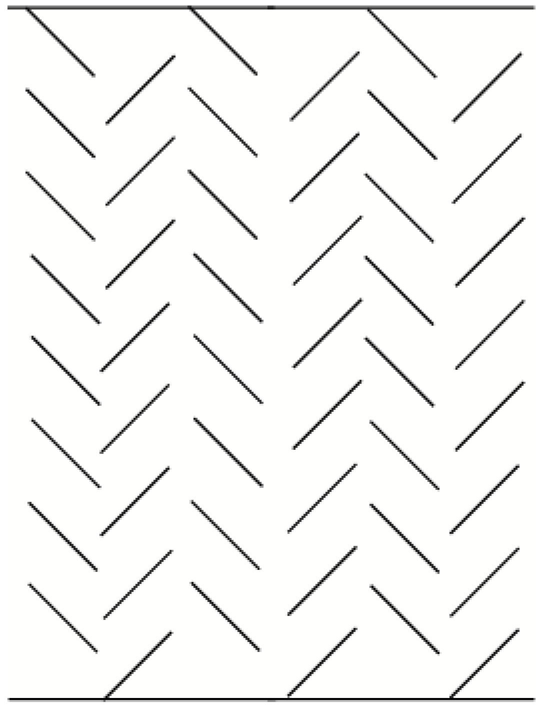


Figure 8: Second example of air inlet

This geometry can also be 3D printed, and offers some of the same advantages as the above example. Both the inlet and outlet can use the same geometry. A test rig will also be developed to check for light tightness.

The inlet must also handle sample insertion. This can be accomplished by using filtered air as a buffered gas to suck in sample air through the venturi effect. The below image shows a possible implementation on a system level. Care will need to be taken in the design to ensure minimal air mixing inside the measurement chamber.

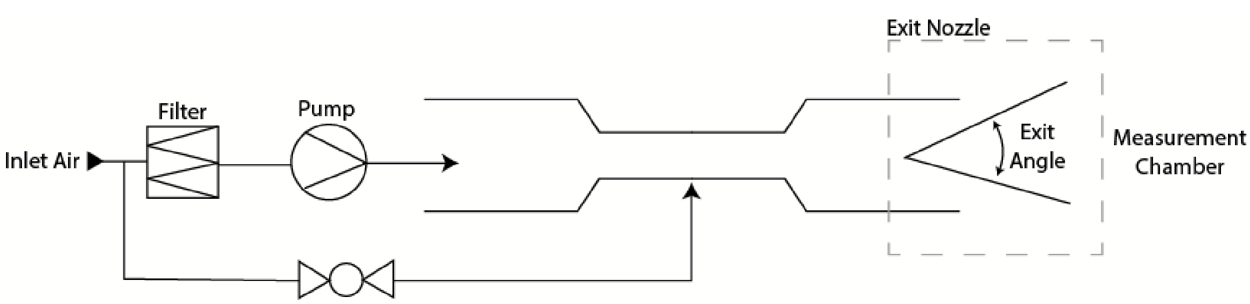


Figure 9: Implementation of sample insertion

The inlet air is sucked in through the narrow section by the venturi effect. The nozzle on the right-hand side will determine the exit angle from the input nozzle. The valve at the bottom controls whether or not the measurement chamber is being purged with air.

In order to design this portion of the inlet, ANSYS fluent will be used to ensure that the exit angle and turbulent flow can be kept to a minimum. The exit nozzle will also need to be modeled using ANSYS fluent.

3.2 Measurement Chamber

Dev 3.2.1 P	Size of chamber must be sufficiently large to differentiate between scattered light and parasitic light
Dev 3.2.2 P	Must be reconfigurable for prototyping many different detector positions, light source positions, and light dumps. (See section 2.1)
Dev 3.2.3 P	Layout of constituent components must be optimal to receive maximum benefit for detection of particles

Table 3: Measurement chamber design specifications

The measurement chamber mirrors the geometry shown in Figure 1. Although we have not come to a conclusive decision as to what the specific layout of the measurement chamber will be (number of detectors, angles, light sources, etc) we have a general idea of how it will be operating. We need to do a complete characterization of detector positions, reflective shapes, and inspect the potential systematics of various choices we may make.

If the measurement chamber is large enough, we may be able to differentiate between light scattered from particles, and the so-called parasitic light which may be detected indirectly from particles. Figure 10 illustrates the concept.

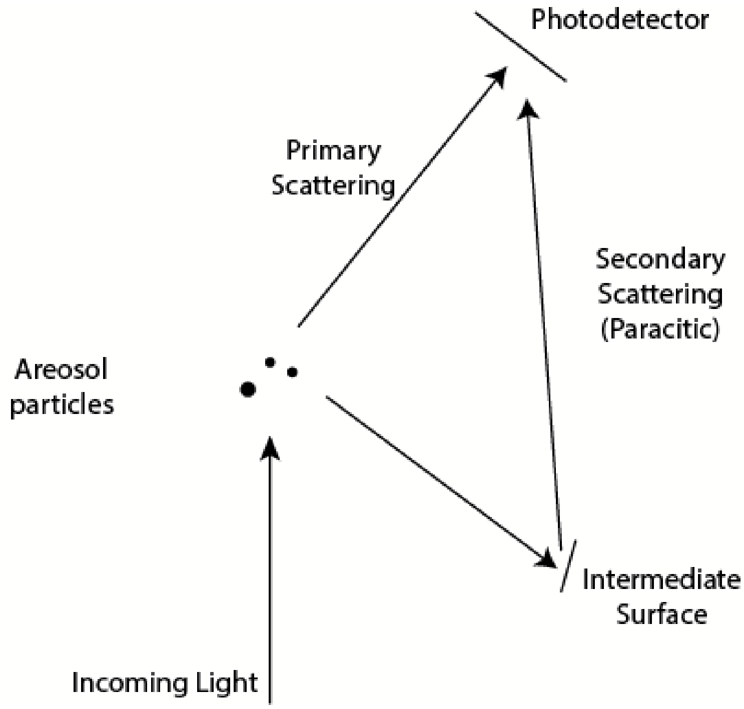


Figure 10: Indirect vs direct light scattering

In the concept above, the parasitic light would take longer to travel to a detector, than a light ray coming directly from a scattering point. We are able to optimize the size of the chamber for discriminating between the two types of light.

3.3 Exhaust System

The exhaust has the same design requirements as the light filter for the inlet system. Refer to the beginning portion of 3.1.

3.4 Light Driver

There is currently a LED driver being developed at TRIUMF for the purpose of fast pulsing of LEDs. Refer to the UBC report for discussion on the previous LED driver.

3.5 Light Source

Dev 3.5.1 P	Particles will be detected using UV sensitive SiPMs
Dev 3.5.2 P	System detects particles that have size larger than the wavelength of the light source ie. geometric scattering

Dev 3.5.3 E	System detects particles that have a similar size to the Wavelength of the light source ie. mie scattering
Dev 3.5.4 P	Wavelength must be between 200 - 400 nm to be UV
Dev 3.5.5 P	Wavelength of light source must be small enough to measure smaller sized particles minimum 0.1 - 0.3 microns
Dev 3.5.6 P	The LED must be able to pulse fast (ns regime)
Dev 3.5.7 P	Low power consumptions

Table 4: Light source design specifications

One of the purposes of this project is attempting to detect particles using UV sensitive SiPMs (See section 3.8). Our apparatus is limited to using light with a wavelength greater than 200 nm light due to UV absorption in the air. There are several UV sensitive SiPMs available on the market which can be used for examples. One example is shown in Figure 11, which is designed to measure atmospheric cherenkov light.

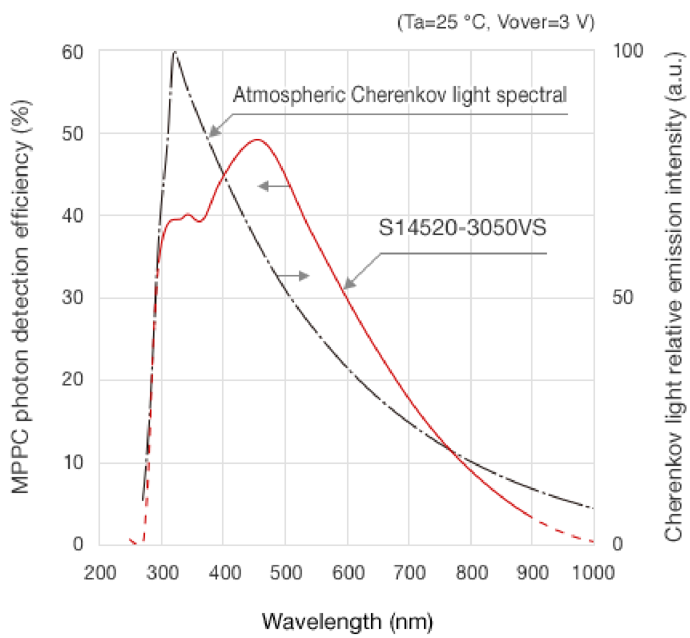


Figure 11: MPPC S14520 series photon detection efficiency

However, in our case, we are using custom designed SiPMs which are more sensitive in the 200-300 nm range (See section 3.8). Thus we can use an LED that is able to emit UV light in the 200 to 400 nm range. CUD5GF1B is an LED manufactured by SETi/Seoul Viosys that emits UV light at 255 nm that is suitable for our design, it costs 200 CAD and can be ordered on digikey. The following information has been extracted from the product's datasheet.

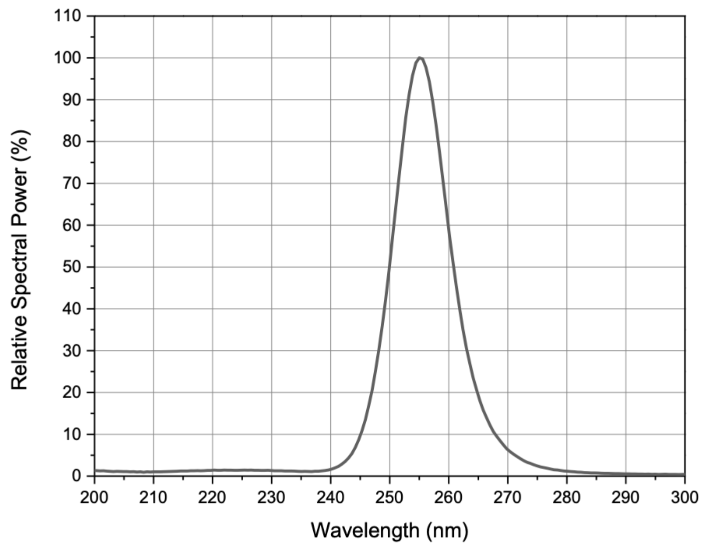


Figure 12 : LED Spectrum, Ta=25℃, IF=100mA

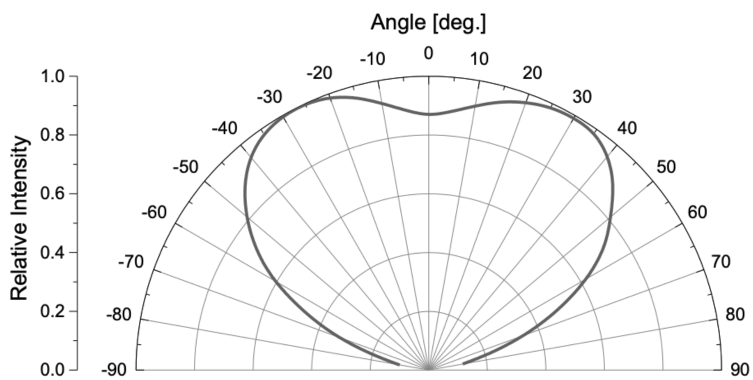


Figure 13 : LED Intensity vs. Angle Distribution, IF=100mA

The intensity vs. angle plot shows that peak intensity is symmetric about the centre and occurs at $\pm 20°$ to $\pm 30°$ from the vertical. More specifications are demonstrated in the tables below (table 5 and 6).

An additional parameter which is often not shown on LED datasheets is the *rise time*. Since we require fast pulsing, this is an important parameter. Thus, during product development in the later stages, we may require purchasing a variety of LEDs which meet the above criteria, and testing their responsiveness.

(T$_a$=25℃, RH=30%)

Parameter	Symbol	Value			Unit
		Min.	Typ.	Max	
Peak Wavelength [1]	λ_p	250	255	260	nm
Optical Output Power [2]	Φ_e[3]	2	3.5	7	mW
Forward Voltage [4]	V_F	5	7.5	8	V
Spectrum Half Width	$\Delta\lambda$	-	11	-	nm
View Angle	$2\Theta_{1/2}$	-	125	-	deg.
Thermal Resistance (J to S) [5]	$R\theta_{J\text{-}S}$	-	31	-	°C/W

Table 5: Electro - Optical characteristic at 100mA

Parameter	Symbol	Value			Unit
		Min.	Typ.	Max.	
Forward Current	I_F	-	-	200	mA
Power Dissipation	P_D	-	-	1.6	W
Operating Temperature [7]	T_{sp}	- 30	-	60	ºC
Storage Temperature [7]	T_{stg}	- 40	-	100	ºC

Table 6: Absolute maximum rating

3.6 Focusing Element

Des 3.6.1 P	High transmission of light from the LED to measurement chamber
Des 3.6.2 P	Control the output of LED to be focused at a specific point
Des 3.6.3 P	Focal point set after sample stream
Des 3.6.4 P	High grade optical material to prevent scattering in lenses
Des 3.6.5 P	Limit scattered light with aperture stops

Table 7: Focusing element design specifications

To prevent light from being scattered arbitrarily from the LED light source, much like on the previous prototype by the UBC group, a focusing system can be used to control the output of light coming from the LED. Since we are operating in the UV region of light, special glass is needed to have a high transmission of light from the LED to the measurement chamber. Many possible materials exist for the transmission of UV light, but for our interest we will use SiO_2. Other materials include LiF, MgF_2, or CaF_2, but they have issues with water solubility, or hard to have good optical grades. The transmission characteristics of various SiO_2 grades is shown below.

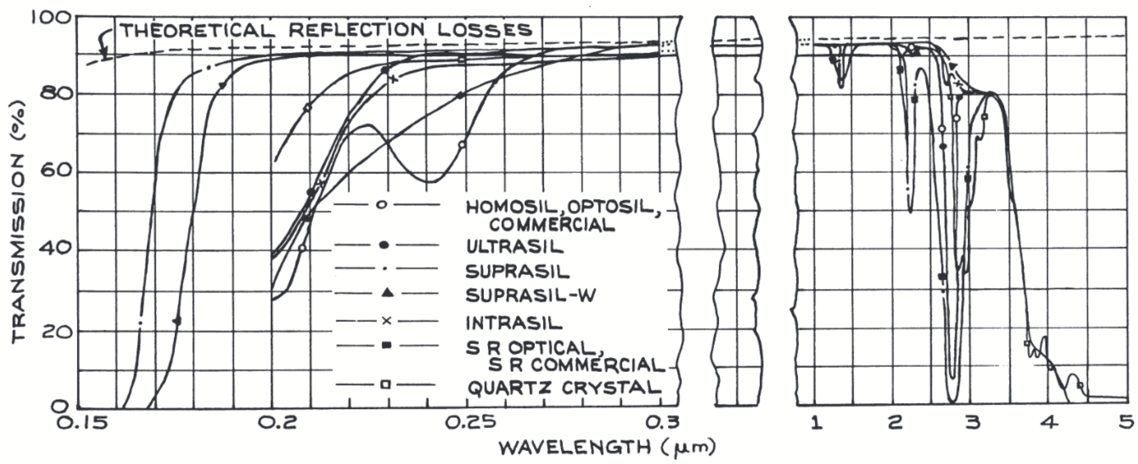


Figure 14: Transmission characteristics of various grades of SiO2. Taken from Ref.[4]

Since we care about optical quality to prevent any parasitic scattering, we want a high grade optical material. Since the focal point is set slightly after the sample stream, we do not care about image quality. This allows us to use cheaper spherical lens geometries in favour of more expensive aspherical elements. Companies such as Esco Optics, Bond Optics, and Edmund optics provide the optical quality and element sizes we need for our focusing elements.

To accomplish culminating the light, and subsequently focusing the light to a point, two plano-convex lenses can be used. The image below shows the layout of the optical system.

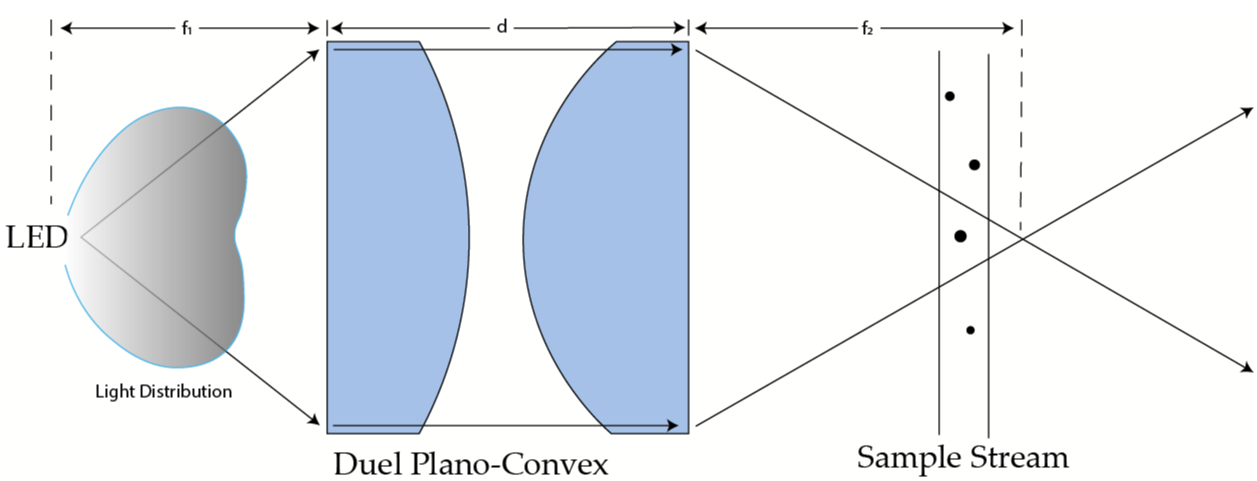


Figure 15: Implementation of optical system

Several aspects of the system can be tailored depending on the rest of the design of the optical chamber. The light output of the LED will determine the focal length and diameter of the first lens, as we want to collect light according to the angular output. The second lens will determine the size of the illuminated area of the sample stream. But for the most part, the choices of f_1, d and f_2 are fairly arbitrary. However, the light trap needs to be able to absorb light of unscattered light, see the next section.

The area between the lenses could potentially have aperture stops to limit the scattered light from the LED.

3.7 Light Dump

Des 3.7.1 P	Trap more than 99% of unscattered light
Des 3.7.2 E	Provide some measure of extinguished light

Table 8: Light dump design specifications

The goal of the light dump is to act as a light trap for all incoming light into its orifice. It may, however, have an additional purpose to measure the amount of extinguished light. The light cone created from the optical system must be fully captured. The image below shows the basic schematic of the light dump.

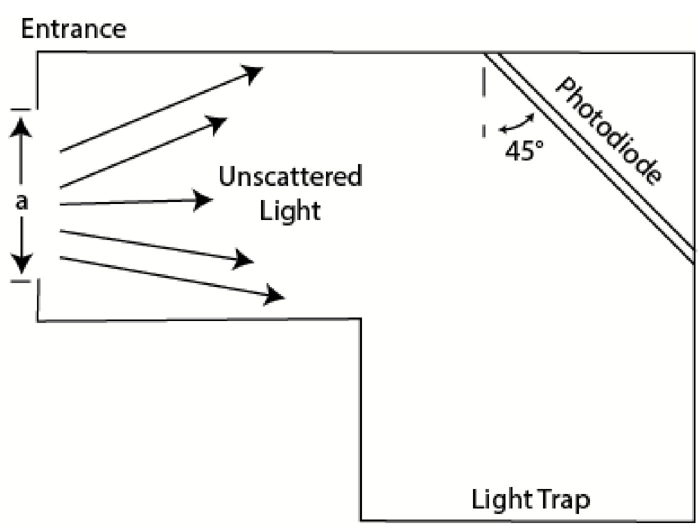


Figure 16: Schematic outline of light dump

The light that enters the dump should eventually either be detected by the photodiode, or collected in the light trap. The photodiode is used to measure the amount of light extinguished from ether absorption or scattering of particles. A potential geometry for the light trap is shown below.

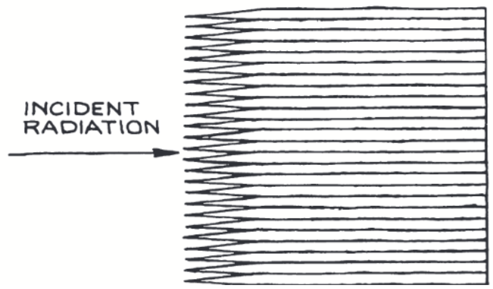


Figure 17: Stacked razor blades light trap. Taken from Ref.[4]

The stacked razer blade geometry can be built into the enclosure if the enclosure is 3-D printed. Otherwise it can be manufactured as an insertable module into the light dump. Light traps can also be commercially purchased from ThrorLabs or Avian Technology.

3.8 Scattered Photon Detectors

Des 3.8.1 P	Needs to be able to produce an appreciable signal from a single photon
Des 3.8.2 P	Needs to be able to produce a signal within the timeframe of each LED pulse
Des 3.8.3 P	Must be able to detect 200-400nm light
Des 3.8.4 P	Darknoise must be below or around 10^6 counts/mm^2/s
Des 3.8.5 P	Rise time must be less than 10ns and settling time must be less than 100ns

Table 9: Scattered photon detectors design specifications

The instrument is operating in the single photon counting range. This means on any given LED pulse, we expect to see only one photon in a detector. This has a number of advantages, as discussed in other sections. Using a photodiode detector without any internal gain provides a signal which is highly susceptible to outside noise. Conventionally, in the case of normal single photon counting, a photomultiplier tube (PMT) is used. However, these devices are big and bulky, and would cause our instrument to be too large for desktop use.

Recent experiments in particle physics have taken an interest in high-gain photosensitive instruments as an alternative to using PMTs. Based on the principle of the Geiger-muller tube, a silicon based version was made to be sensitive to a single photoelectron called a single photon avalanche photodiode (SPAD).

In the silicon case, an electron is produced by the photoelectric effect in the space charge region. This electron is accelerated through a multiplication region where many more electrons are generated, and then all the electrons are collected at a terminal. The multiplication region can apply a gain of roughly 10^6. The avalanche induced by the photoelectron is then quenched by an exterior resistor. Pulse timings can range from sub nanosecond, to tens of nanoseconds depending on the size of the SPAD or the size of the quenching resistor.

An array of SPADs makeup what is called the silicon photomultiplier (SiPM), and the intensity of the incoming light is determined by how many SPADs fire at once. See the figures below for details.

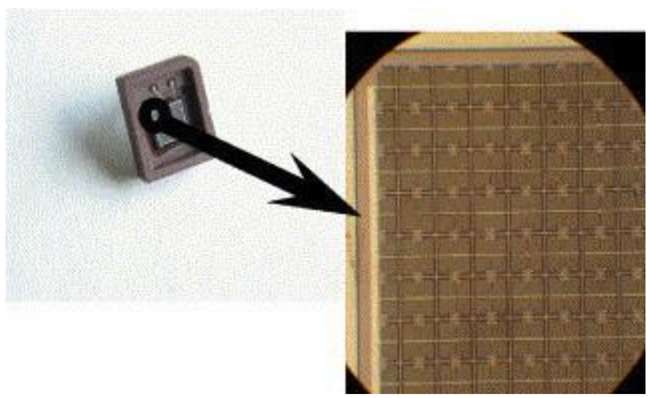


Figure 18: Closeup showing an array of SPADs (right) which makeup a SiPM (left). Taken from Ref.[2]

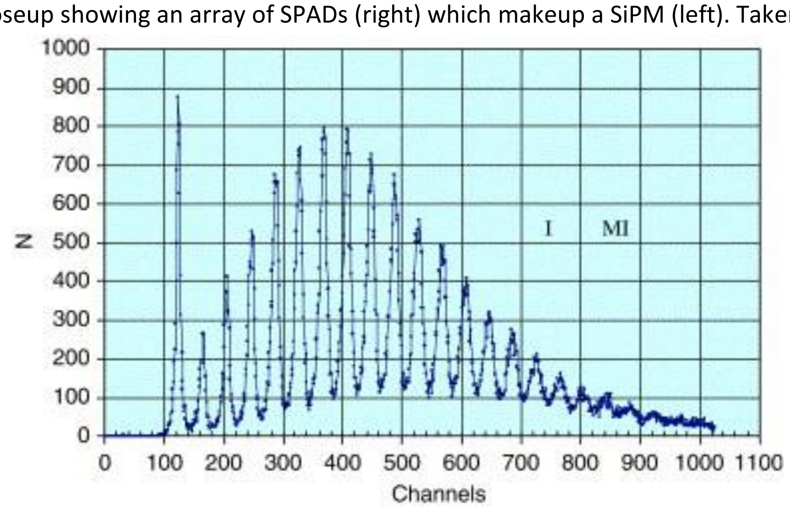


Figure 19: Number of pulses vs pulse height of a SiPM. The discrete nature and narrow widths of the peaks correspond to how many SPADs in the SiPM were firing. Taken from Ref.[2]

For SpecTro, we are using custom designed SiPMs which are specialized to measure UV light in the range of 200-300nm. See section 3.5 for the criteria of light sources which can produce pulsed UV light. The driver circuit for these is also being designed in house at TRIUMF. Based on the principles of SiPMs outlined above, these devices will act as ideal light detectors, and as such, they were used in the previous prototype by the UBC group.

There are a few systematics of concern when working with SiPMs. The generation of dark noise (random firing of a SPAD) can happen as high as 10^6 triggers/s/cm^2. The dark noise can be mitigated through cooling the SiPMs, or by using short pulses of light. Cross talk between neighbouring SPADs can cause one photon to look like several different pulses. There is usually some delay between SPADs triggered by external light, and those who are caused by neighbouring cells. Again, this can be mitigated by correlating the short LED pulses and signals measured by the SiPMs. One last major concern is that of after pulses. Electrons can become trapped in the photosensitive region, and migrate to the multiplication region after some time. Again, correlation can mitigate this systematic as well.

The basic information we have on the SiPMs is as follows. The active area is a 3x3mm detection area, with the option of adding together arrays into a 6x6mm active area. The photon detection efficiency is around 25% at 250nm. And the response time is around 1ns, with a fall time of 50ns.

For a more indepth review of SiPMs, please see Ref.[3].

3.9 Data Acquisition System

Des 3.9.1 P	Multiple counts (detections) per LED pulse at 100 kHz
Des 3.9.2 E	Results written to SD card
Des 3.9.3 E	Results extracted using Wi-Fi/Bluetooth/USB
Des 3.9.4 E	Counts are processed in the HPS

Table 10: Data acquisition system design specifications

This section will discuss the calculations needed for analysis of the system and how to accomplish the need for very fast calculations and storage. There are two calculations that are needed. Firstly, we need to obtain the count of detections per LED pulse at 100kHz. This calculation will help us mitigate dark noise (false detections) and analyse the number of particulates that can be detected per pulse. Secondly, we need to acquire the period of time a concentration of a particulate is detected in the air. This calculation will grant us the knowledge of how long a particulate remains in the air, this additional information can be very useful for testing the system and analysis for the consumer.

These calculations need to meet frequency constraints that will be accomplished by a Cyclone V SOC FPGA. This FPGA was chosen because of the hard processor system (HPS) which will allow us to analyse, manipulate and time stamp our calculations from the FPGA. The flow of information begins with the detector sending a signal to the comparator and based on a threshold, the comparator will send a HIGH signal to the FPGA through the GPIO pins to indicate a detection. The FPGA will collect the data in unsigned vectors and after every LED pulse the information will be sent to the HPS through the FPGA to HPS bridge where it will be manipulated and further stored in the SD card. The results will be later extracted at 10 second intervals on an external device; this is because getting the information immediately from the FPGA is slow which would result in the loss of information.

A general output in a buffer will be stored on the SD card detailing the date and time for the transaction and bin (range of angles) counts. The information can be extracted to an external device using USB, bluetooth or Wi-Fi.

Figure 21 shows the connection between the FPGA fabric to the L3 interconnect to the HPS. It also includes the data widths and the corresponding clock domains. FPGA-HPS bridge will master the L3 main switch, this grants the masters in the FPGA fabric access to the slaves in the HPS [5].

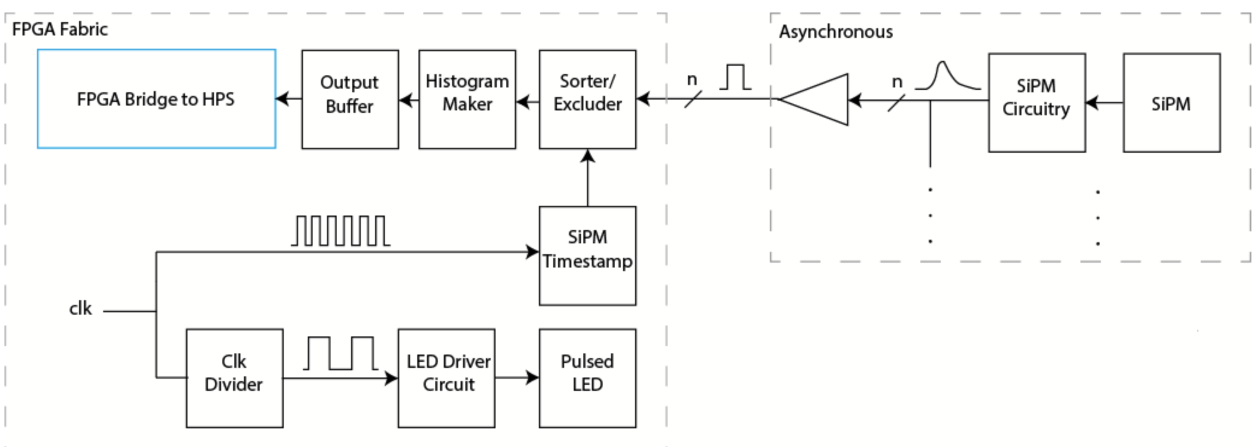


Figure 20: Block diagram visualizing the flow of information from Detector to FPGA bridge

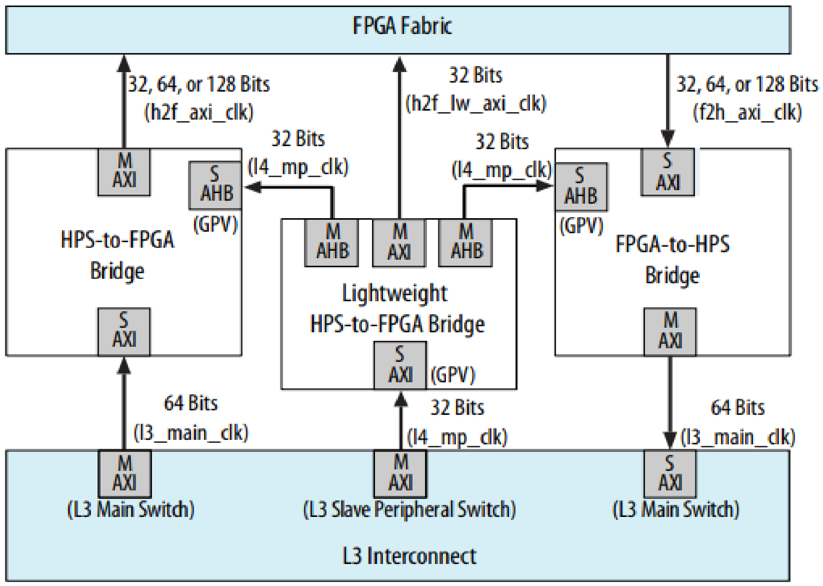


Figure 21: Detailed representation of FPGA to HPS [5]

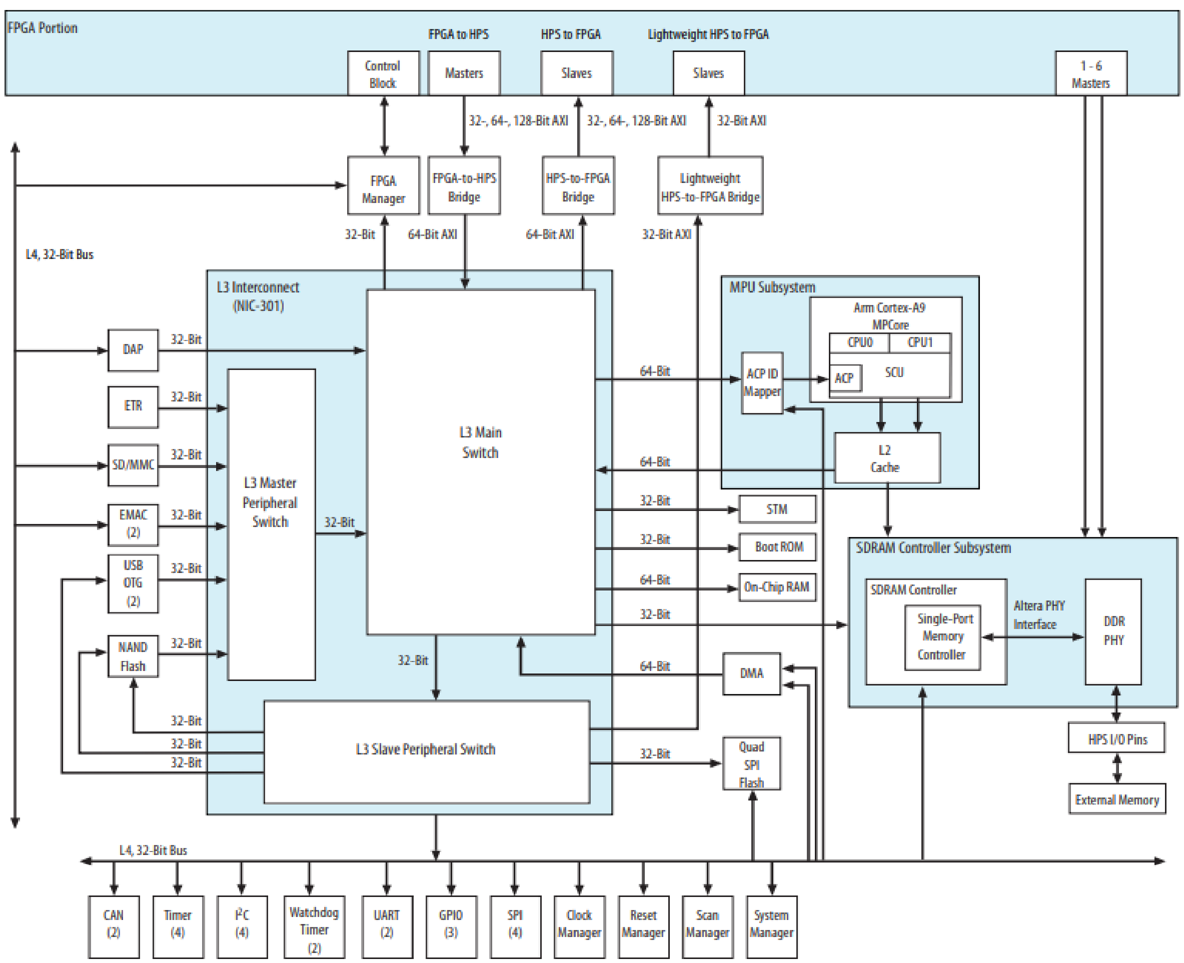


Figure 22: Cyclone V block diagram [5]

4 Control Requirements

The section processes the information from the data acquisition system. A block diagram showing the various instruments is shown below:

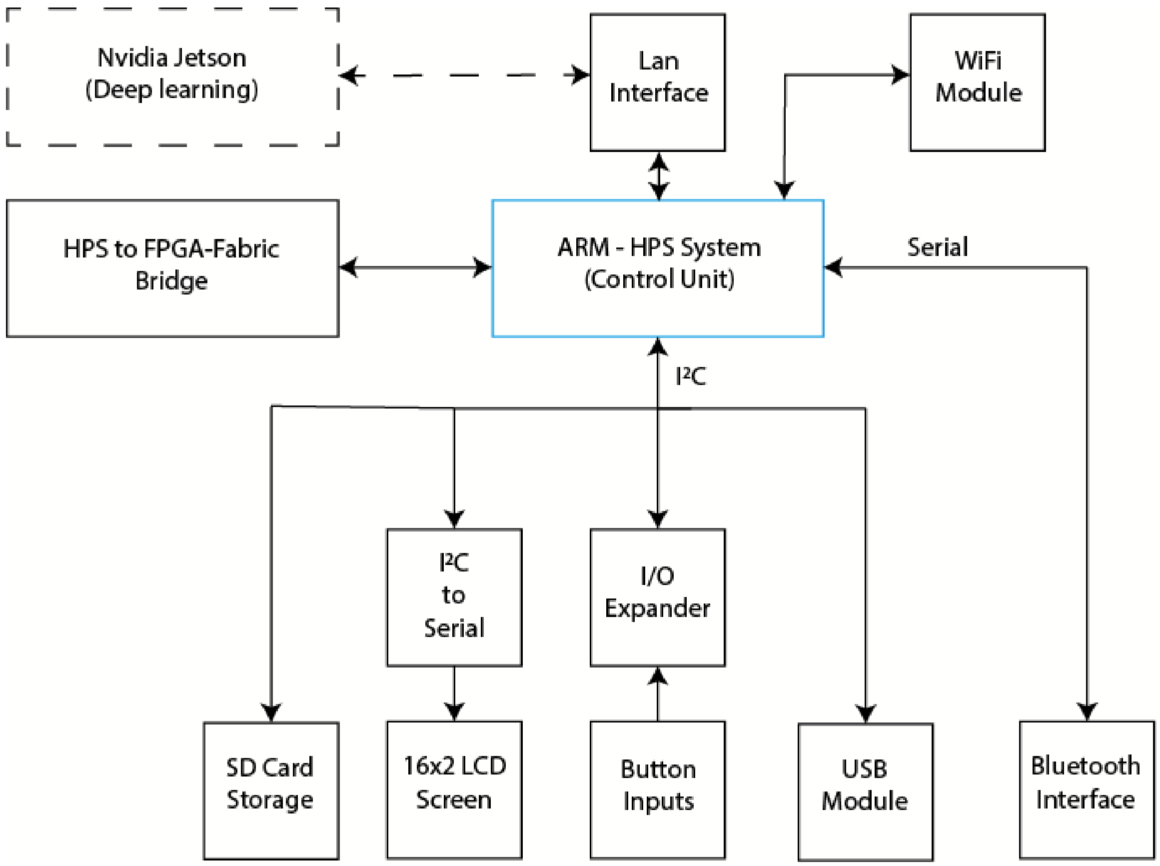


Figure 23: Outline of the control system, and its interconnects

4.1 Control Unit

Des 4.1.1 E	The Control Unit must be able to manage many different components (LCD screen, bluetooth/Wi-Fi modules etc.)
Des 4.1.2 E	The control unit must not lock up or hang unexpectedly (more than 99% reliable)

Table 11: Control unit design specifications

As we are utilizing a Cyclone V SoC system for our DAQ processing, the HPS is ample for acting as the control unit for the board. Many board addons have been developed for the Raspberry PI, which is another ARM based computer. This allows us to find addon boards with ease, such as

2x16 LCD screens, or communication modules. In the next sections, we will detail how we may be able to accomplish this using pre-existing hardware.

4.2 User Input

Des 4.2.1 E	Buttons are big (16 mm) and comfortable
Des 4.2.2 E	Buttons compatible with I2C communication protocol
Des 4.2.3 E	Use I2C to GPIO (I/O expander) module

Table 12: User input design specifications

Buttons and a screen provide the best way for a user to interact with the system without any external connection. The buttons must be large enough to be easily pushed by a user standing nearly arm's length away. Many large buttons exist on the market.

Figure 24: 16mm momentary push button. Can be purchased at Ref. [14]

A button multiplexer can be used, such as the LM8330 module, which interacts with a host of buttons on one side and is compatible with the I^2C communication protocol. However, the LM8330 module is a complicated chip for using just four buttons. A generic i2c to GPIO, a so-called I/O expander, is a much better chip for prototyping our device, as it allows for other devices to be used in the event of additional features needed.

Another possible implementation would be to utilize some pins on the GPIO for the FPGA, and interact through the HPS-FPGA bridge. However, in the interest of keeping the DAQ circuit and control unit separate, the above two options should be explored first.

4.3 Status Screen

Des 4.3.1 P	Readable output on the screen with large font
Des 4.3.2 P	LCD screen has I2C pinout

Table 13: Status screen design specifications

The status of the communication unit can be shown using a 16x2 LCD screen, which has a large font, and is largely readable. Commercial models exist which already have I^2C pinout, and conversion modules exist for those who do not. The user interface on this screen will be explored in the UI/Device appearance appendix.

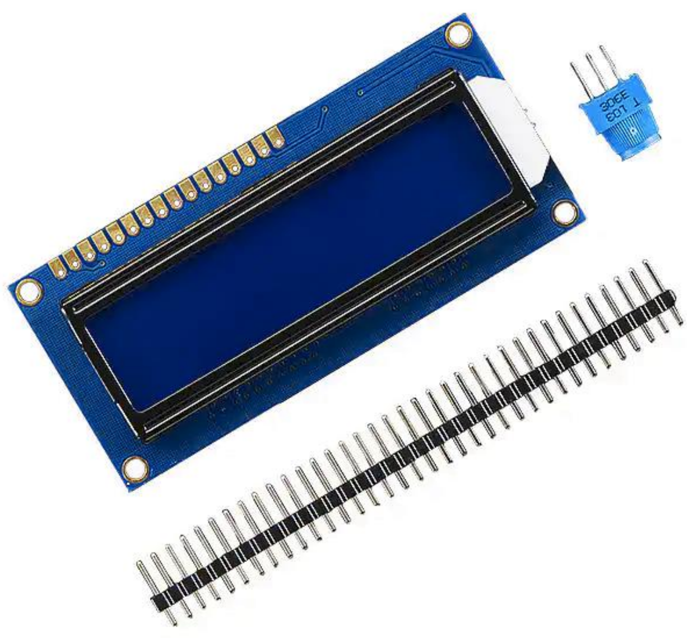


Figure 25: Standard 16x2 LCD Module. Can be purchased at Ref. [15]

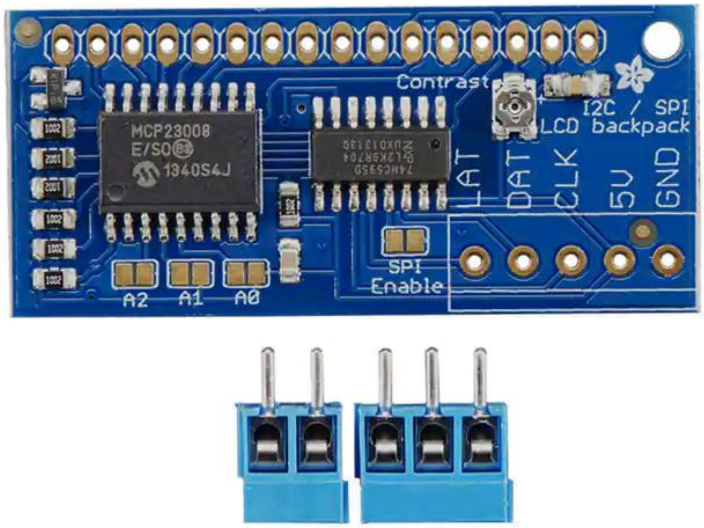


Figure 26: Serial to I^2C conversion board for 16x2 LCD screens. Can be purchased at Ref [16]

Pending the size of the instrument, we may be able to use a smaller, and more feature rich, OLED screen. However, the font size is quite small, so we can only use this screen if the user is intended to be visually close to the instrument. Based on our current assessment of what the instrument could resemble, the 16x2 LCD module is a much better choice. However, for brevity, we include a possible OLED module for future prototypes.

Figure 27: Four pin I2C 1.3" 128x64 OLED. Found at Ref. [17]. However, many other modules exist on the market.

4.4 Communication Medium

HM10 Bluetooth Module

Des 4.4.1 E	Bluetooth module can communicate with the FPGA through UART serial communication
Des 4.4.2 E	Bluetooth has transmission rates 2.1 Mb/s
Des 4.4.3 E	Bluetooth power consumption is low: Operating Current: 40 mA
Des 4.4.4 E	Bluetooth module has wireless communication of less than 100 meters

Table 14: HC06 bluetooth module design specifications

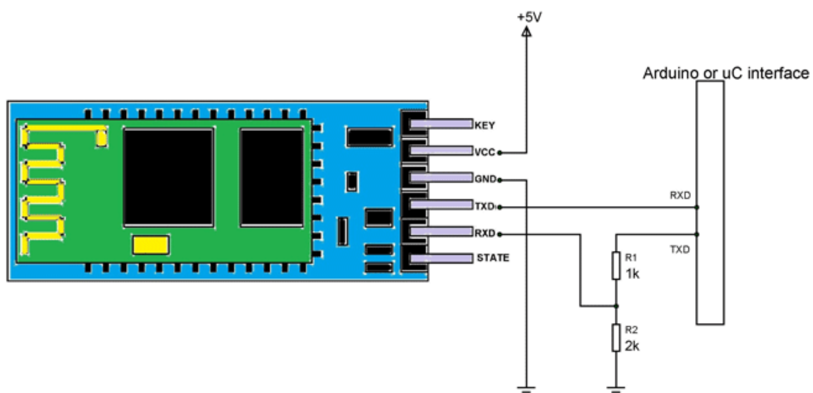


Figure 28: Schematic layout of bluetooth module [9]

The system must have bluetooth connectivity that provides the consumer the capabilities to connect with the device. For our needs Bluetooth 2.0 is sufficient because all smartphones will be able to connect and the module supports the data rate for the transmitted information. We expect to send 255 bins of data at 16 bit depth per bin; the expected output is 4088 bits. 4088 bits meets the requirements of the data transfer rate of 2.1 Mb/s. This bluetooth module only acts as a slave so it will be able to transmit requested data and receive data from the master device (smartphone). This module also consumes less power to function and it is a cheap solution for our device. The Cyclone V SOC has a UART interface and the HC06 can communicate over UART[9]. The price is approximately $3.88 CAD on Ebay.

ESP8266 WI-FI Module

Des 4.4.5 E	Wi-Fi module has integrated TCP/IP protocol
Des 4.4.6 E	Wi-Fi module supports SDIO 2.0, SP, UART
Des 4.4.7 E	Wi-Fi module has Wi-fi Direct peer to peer wireless connection
Des 4.4.8 E	Wi-Fi module has 2ms, connect and transfer data packets
Des 4.4.9 E	Wi-Fi module has low power consumption
Des 4.4.10 E	Wi-Fi module has 2.4 GHz transmitter and receiver

Table 15: ESP8266 WI-FI module design specifications

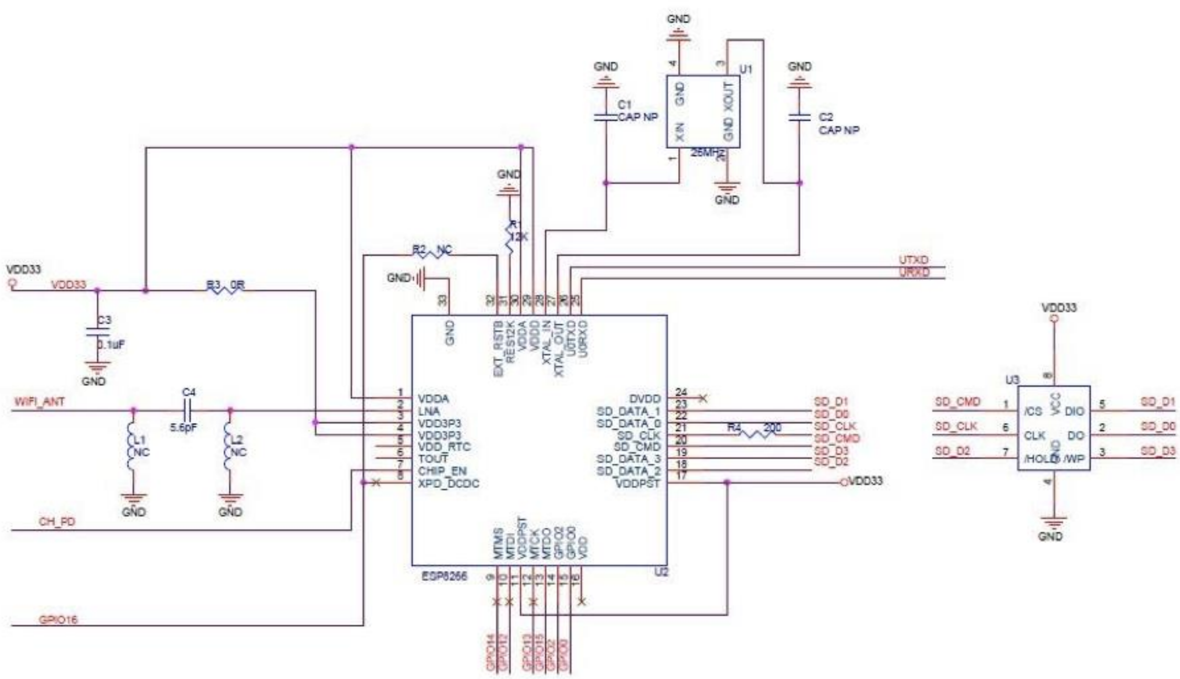


Figure 29 : ESP8266 schematic

The second mode of wireless communication will be committed through Wi-Fi. ESP8266 is a Wi-Fi module that meets our basic needs for transmitting data over a network. It has TCP/IP protocol and P2P connectivity. It has 5 different states that help exercise low power consumption: off, deep sleep, sleep, wake and on. The three states in the middle are the power management capabilities of the module. The radio receiver and transmitter work at 2.4 Ghz which is sufficient for our needs. The price of the module is cost effective as it is only $6.95 american [8].

USB Module

Des 4.4.11 E	USB-I2C module has drivers for Windows, Linux, and OSX
Des 4.4.12 E	USB-I2C module provides complete interface between your pc and I2C bus
Des 4.4.13 E	USB-I2C module provides 70 mA at 5v from external circuitry from a standard 100 mA port

Table 16: USB module design specifications

Many boards use the FTDI FT232R USB chip, which is an I^2C to USB bridge. As the HPS system has a I^2C controller, this chip is adequate for providing USB connectivity for the device. The data rates will match the USB version. USB 2.0 will provide 480 Mbps data rate transmission which will be adequate for our system [7].

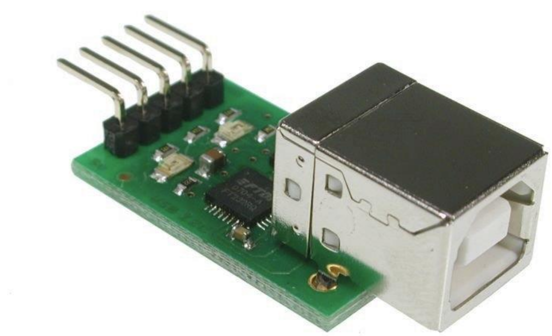


Figure 30: USB to I^2C module. The module can be purchased here: [6]

Conclusion

In this document, the design specifications of SpecTro are discussed, the basic principle of detection and analysis of air particulates. Different properties are analyzed such as shape, size, and concentration. This document provides justification for the design choices our team has made as well as an explanation for the underlying principle to the operation of SpecTro. This will serve as a reference document for photonicEyes as the team begins developing the Proof-of-Concept Prototype for SpecTro in the near future. We tried to ensure our design specifications are made true by paying attention to detail. Although, during the prototyping phase if photonicEyes discovers that an aspect of our design is not suitable; we may revise this document appropriately throughout the development cycle to ensure correctness.

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Appendix A: Supporting Test Plan

Introduction

This appendix section specifies the details of the design verification test plan for SpecTro. It includes tests for the user interface, hardware, software, and mechanical tests to ensure robustness of the system.

User Interface Testing

The following set of tests will be performed on the user interface of SpecTro. They will ensure the system functions according to requirements as well as design specifications.

Test Name	Successful signup
Test Description	Click signup button when prompted with the login screen, enter information and create a unique username along with a password, click create account.
Expected Outcome	An entry is created on the database linked to the correct username.
Actual Outcome	

Test Name	Successful login
Test Description	Enter previously created account information (username and password) when prompted with login screen and click log in.
Expected Outcome	The user successfully logs in to their account.
Actual Outcome	

Test Name	Forgot password
Test Description	Click on “forgot password?” from login prompt
Expected Outcome	This will redirect you to a page which will ask for your email address with which the account was initially created, and a link will be sent to your email to reset your password.
Actual Outcome	

Test Name	Navigating the menu
Test Description	Click on different menu options in the left column after a successful login.
Expected Outcome	Each menu item should take the user to the appropriate screen.
Actual Outcome	

Test Name	Successful logout
Test Description	Click the x button in the top right hand corner.
Expected Outcome	The user is prompted with the option to logout. Confirming the prompt should successfully logout the user from their account.
Actual Outcome	

Test Name	Successful FPGA connection
Test Description	Connect the FPGA to the detector
Expected Outcome	The radio button should light up green after the connection to the FPGA is successfully established.
Actual Outcome	

Test Name	FPGA connection issue
Test Description	Disconnect the FPGA
Expected Outcome	The “Start” button should turn grey and you should not be able to start the detection process.
Actual Outcome	

Hardware Testing

In this section we will describe a set of tests to be done on a small group of select products. These tests address the performance of individual subsystems.

Test Name	Particle admittance (Dev 3.1.2)
Test Description	Remove the air inlet. Apply a 0.1-10 um aerosol test source and begin measurement. Stop measurement, and reaffix air inlet. Perform test again.
Expected Outcome	Program should report only a slight decrease in concentration in 0.1-10 um particles present (No less than an order of magnitude).
Actual Outcome	

Test Name	Light Trap Effectiveness (Des 3.7.1)
Test Description	Turn the sample air valve off to only blow filtered air into the measurement chamber. Allow filtered air to flow at least 5 min before the beginning of this test. After 5 min, begin measurement.
Expected Outcome	Every SiPM should report less than 10^7 counts/cm^2/s
Actual Outcome	

Test Name	SiPM Darknoise Evaluation (Des 3.8.4)
Test Description	Disable LED light source, cover both inlet and outlet. Run the dark noise measurement program and record the darknoise rate for each SiPM.
Expected Outcome	Every SiPM should report darknoise less than 10^6 counts/cm^2/s
Actual Outcome	

Test Name	Bluetooth Module
Test Description	Turn on the bluetooth module in pairing mode. Turn on bluetooth on a smartphone. Connect the smartphone to the bluetooth module via bluetooth.
Expected Outcome	Bluetooth connection is established between the two devices
Actual Outcome	

Test Name	Wi-Fi Module
Test Description	Turn on the Wi-Fi module. Turn on Wi-Fi on a smartphone. Connect the smartphone to the FPGA via Wi-Fi module.
Expected Outcome	Wi-Fi connection is established between the two devices
Actual Outcome	

Test Name	USB module
Test Description	Connect the USB end to the computer. Use the I2C to USB module to connect the I2C end to the FPGA.
Expected Outcome	Connection is established between the two devices via USB.
Actual Outcome	

Test Name	Operational testing
Test Description	Use device for 1 year
Expected Outcome	Device should still be operational
Actual Outcome	

Software Testing

The following set of test cases will test the performance of the software running on specTro. They will ensure the algorithms function according to requirements and design specifications.

Test Name	Starting detection
Test Description	Click start detection button
Expected Outcome	The LED should start pulsing and SiPMs should start collecting data. The data processing should start. The analysis results are shown on the screen in the form of a pie chart in less than 3 seconds.
Actual Outcome	

Test Name	Correct analysis
Test Description	A pre-known amount of soil dust is allowed inside the chamber. Start detection button is pressed.
Expected Outcome	The analysis results reflect the correct amount of dust in the form of a percentage.
Actual Outcome	

Test Name	Changing settings
Test Description	Change parameters inside the settings menu
Expected Outcome	Modified parameters are printed on screen
Actual Outcome	

Test Name	Error handling (connection issue)
Test Description	Disconnect FPGA during detection
Expected Outcome	Error should be handled gracefully with the correct error message on the screen.
Actual Outcome	

Test Name	Stress testing
Test Description	Click the start detection button and leave the device in detection mode for 24 hours
Expected Outcome	System must not crash and results should accumulate over the entire 24 hour period
Actual Outcome	

Appendix B: User Interface and Appearance

Introduction

This appendix will extract the design of SpecTro's user interface and appearance of the device system. We will explain the design choices for the user interfaces, analyze how our users will use the product, and discuss design considerations based on Don Norman's Seven elements of UI Interaction.

Purpose

The main objective of this appendix is to explain the design of SpecTro's user interface and provide an overview of the UI's main components and their functionality.

Scope

This appendix will focus on the prototype's user interface. It contains an analysis on our users and how they will interact with our device.

User Analysis

The targeted users of this product are industrial stakeholders with influence on manufacturing devices accountable for air-quality diagnostics and demonstrations. This type of equipment is usually very expensive and we are aiming to provide a solution that is cost efficient. The design of SpecTro's UI is very simple and straight-forward, so this might be a plus point for users. At first we set up a login prompt so the user can sign up a new account or login with their username and password to the main page which will provide several menus such as: Home, Information, Detection, Sample chart and Settings, etc. However, the user will be able to demonstrate our prototype in detail from the information menu to understand all the reliable materials used in our system. The user can start the detection process from the 'Detection' menu and can check the graphical chart of the sample detected from the 'Sample chart' option. The user can also change the configuration of the interface from the 'Settings' menu.

Technical Analysis

This section discusses SpecTro's user interface based on Don Norman's Seven elements of UI Interaction. This includes the following design factors: discoverability, feedback, conceptual models, affordances, signifiers, mappings and constraints.

- Discoverability encloses how easily a user can locate various user interface elements when they are using the product for the first time, and discover what they can do with these options, buttons and other elements. We tried to design our user interface with minimalism and simplicity to avoid confusion and so that it is user-friendly. For instance, some users might not have an idea about the light source of our device, our interface carries an information panel with a variety of sub-menus like particle properties, FPGA calculation, light source and lens system.
- Feedback refers to signalling to the user to notify them of changes or the status of the system. In order to ensure this, we are planning to set up some LED on our air particle detector that will notify of its state in the user interface. For instance, when the detector is powered on and connected with the FPGA with all other GPIO connections, the LED will turn on which will lead the radio button to turn green in the 'Detection' panel beside the line "The detector is connected with the PPGA" shown in figure 32.
- Conceptual model is a representation of a system, made of the composition of concepts which are used to help people know, understand or simulate a subject the model represents. Our design would project the information needed for the user to intuitively understand how to use the device's features and capabilities. Prior experience with using electronic devices related to demonstration of particulates or the information panel in our UI will help the user build a conceptual model of our device and the substance it will be dealing with.
- Affordance is a property or feature of an object which presents a prompt on what can be done with this object. It relates to how intuitive an object in the interface is to use. Our UI buttons are very well-labelled which will help guide the users what each button does.
- Signifiers are similar to feedback which provides extra information on how to use the product's main features. PhotonicEye's signifier includes an LED on the device to indicate that the device should be connected with the FPGA in order to start the detection. Common symbols for UI elements in this case is the change of color for the radio button in the detection menu to provide the user with extra information on when to start the detection process.
- Button mapping describes for the user to easily understand the purpose of a button in the device or the functionality of the UI. Since our product is a detector, the basic usage of it should be simple. There will not be that many buttons in the device for user input, and the buttons that we will have will be well-labeled and perform simple tasks (e.g. power, up, down, enter and back button to navigate the detection operations shown in Figure 35).
- Constraints limit or restrict the number of choices a user can choose to act upon. For example, the detection process cannot start until the GPIO and FPGA are connected with

the detector. However, the detection will not perform appropriately if the optical chamber is not air-tight.

Engineering Standards

Our objective is to create the most instinctive user interface for photonicEyes for which the following Engineering Standards will be followed throughout the development of the prototype and the user interface:

Standard	Description
ISO 9241-161:2016	Ergonomics of human-system interaction — Part 161: Guidance on visual user-interface elements [19]
IEEE 1621-2004	IEEE Standard for User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments [20]
ISO 9241-210:2010	Ergonomics of human-system interaction — Part 210: Human-centred design for interactive system [21]
RoHS Compliance	Restriction of Hazardous Substances [22]
CAN/CSA-C22.2 No. 250.13-17	Light emitting diode (LED) equipment for lighting applications [23]
CAN/CSA-C22.2 No. 61508-1:17	Functional safety of electrical/electronic/programmable electronic safety related systems, Part 1: General requirements [24]
IEC TR 62471-2:2009	Photobiological safety of lamps and lamp systems - Part 2: Guidance on manufacturing requirements relating to non-laser optical radiation safety [25]

Table 17: User interface engineering standards

Analytical Usability Testing

This section outlines the analytical usability testing procedures that Spectro's engineer will perform for quality assurance of the UI and UX. This can help us evaluate the solutions of the problems present in our interface and appearance mode.

Login page:

Our user interface has a login page for the user to login to the main page with their username and password. A new user can sign up to use the interface for confidentiality.

Main Page:

Our Main page contains few options and sub-options.

Home: This option lets the user know a detailed overview of the user interface and the system.

Information: If the user is not familiar with the substance we are detecting, they can use the sub-options under the information panel to know about things like properties of the particulates, the use of FPGA, information about the light source and the optical chamber.

Detection: The main purpose of this interface is the detection. The user can operate this process if the FPGA is connected with the detection device and all other peripheral inter-connections. The disconnection will not give the user the options to start a detection process shown in Figures 32 and 33.

Sample chart: After detection, the user can check on this page for the status and distribution of the detected particulates in the surroundings.

Settings: This option gives the user to change the configurations of the interface.

LCD Menu:

Info Screen: Shows basic information such as uptime and current particle concentrations.

Logging: Setup data logging for offline processing

Connection: Setup/disable connections, and check the status of external connections

About Screen: Firmware version, and contact information

LCD Buttons:

Up/Down: Users can manually navigate the options on the LCD screen to choose between the menus.

Enter: While navigating the user can select a menu option by pressing this button.

Cancel/Back: If the user wants to discard an operation or go back to the previous menu.

Empirical Usability Testing

This section will discuss the empirical testing procedures that will be performed by end users. Since feedback plays a significant role for the development of the product, we plan to take assessment from our target market once the test steps are performed based on our user interface design. During the development phase of our prototype, our team would assess the state of the design to deliver possibilities for optimizing the user experience.

Feedback questions:

1) Was the setup process for making all the connections to the instrument difficult to carry out?
2) Did you face any difficulty while starting the program?
3) Was the interface in the LCD straightforward and easy to use?
4) Do the buttons work perfectly when navigating and operating the LCD screen?
5) After starting the process, were you able to observe expected amounts of aerosol concentration?
6) Did you face any difficulty while logging in to the UI made for the PC?
7) Was the main page of the UI user friendly?
8) Does the UI cover all the necessary aspects in the information panel for the operation?
9) Can you start the detection process smoothly when the GPIO is connected?
10) Does the radio button in the detection panel of the UI turn green when the GPIO is connected?
11) Can you pause and start again while the detection is processing in real time?
12) Does the sample chart panel give you the correct and updated data representation for the recent detection?

Graphical Presentation

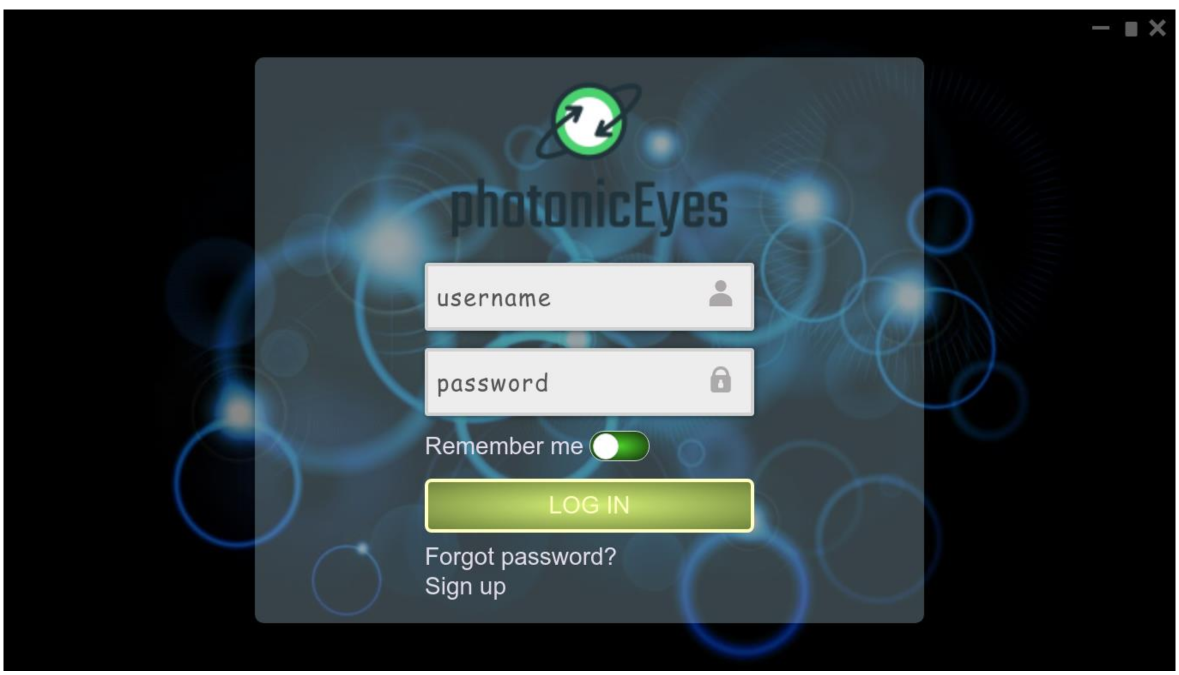

Figure 31: Login prompt for SpecTro

Figure 31 shows the login prompt which asks for valid credentials to access the device. If you are new to the system, you will need to sign up first by providing a valid username and password.

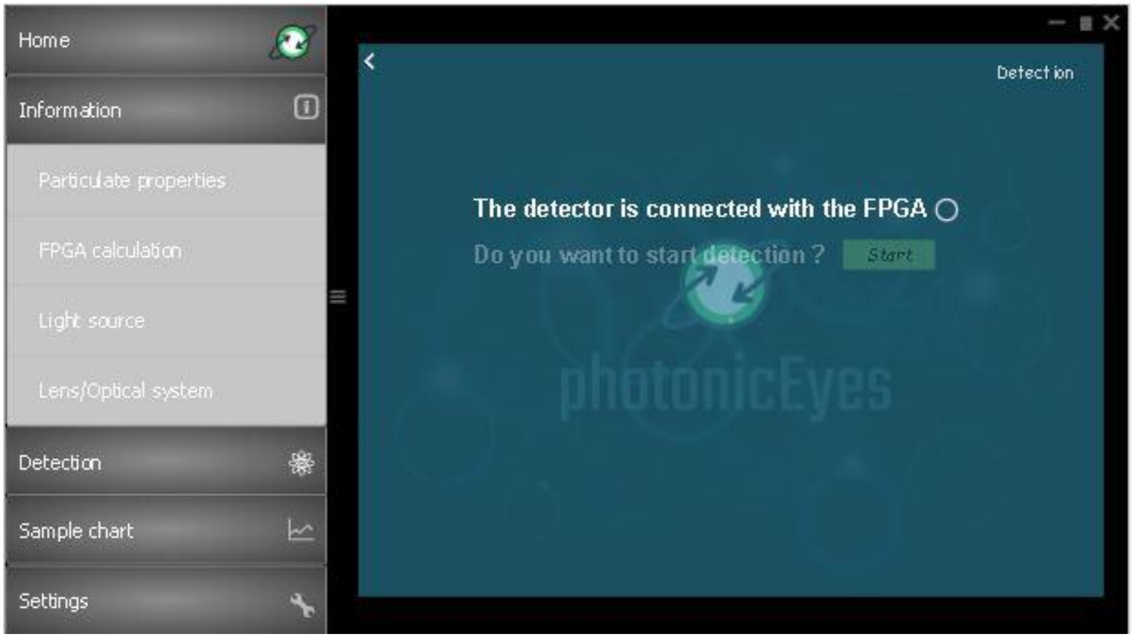

Figure 32: Detection panel without establishing FPGA connection

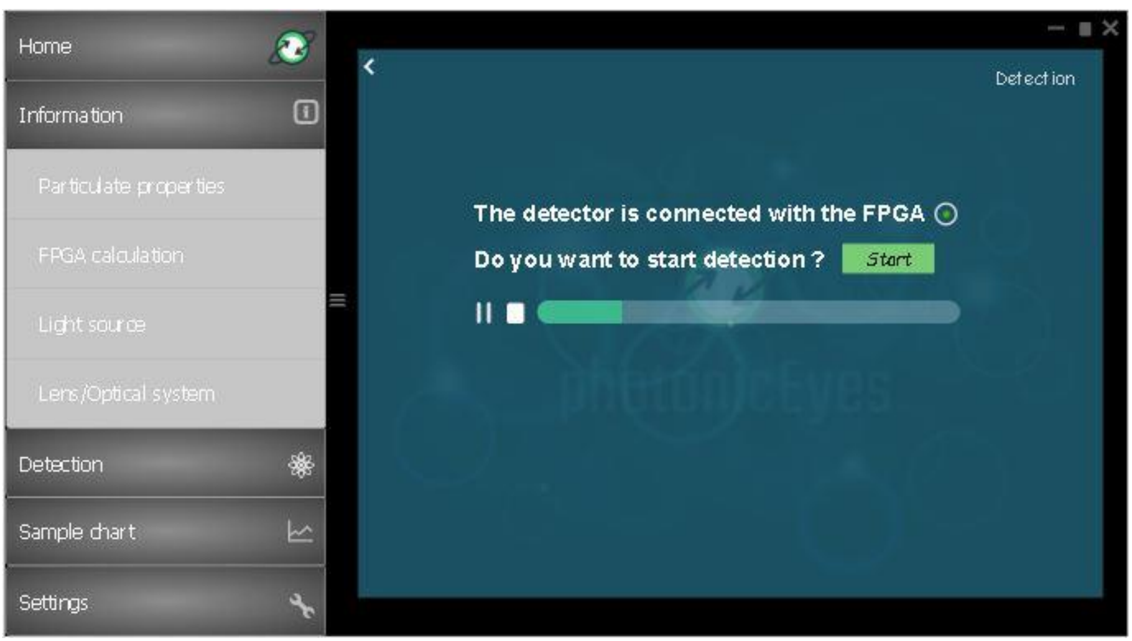

Figure 33: Detection panel after establishing FPGA connection

The radio button will be empty if the FPGA is not connected to the detector yet which is shown in Figure 32. However, the radio button turns green when the FPGA is connected and the detection process is ready to start, as shown in Figure 33.

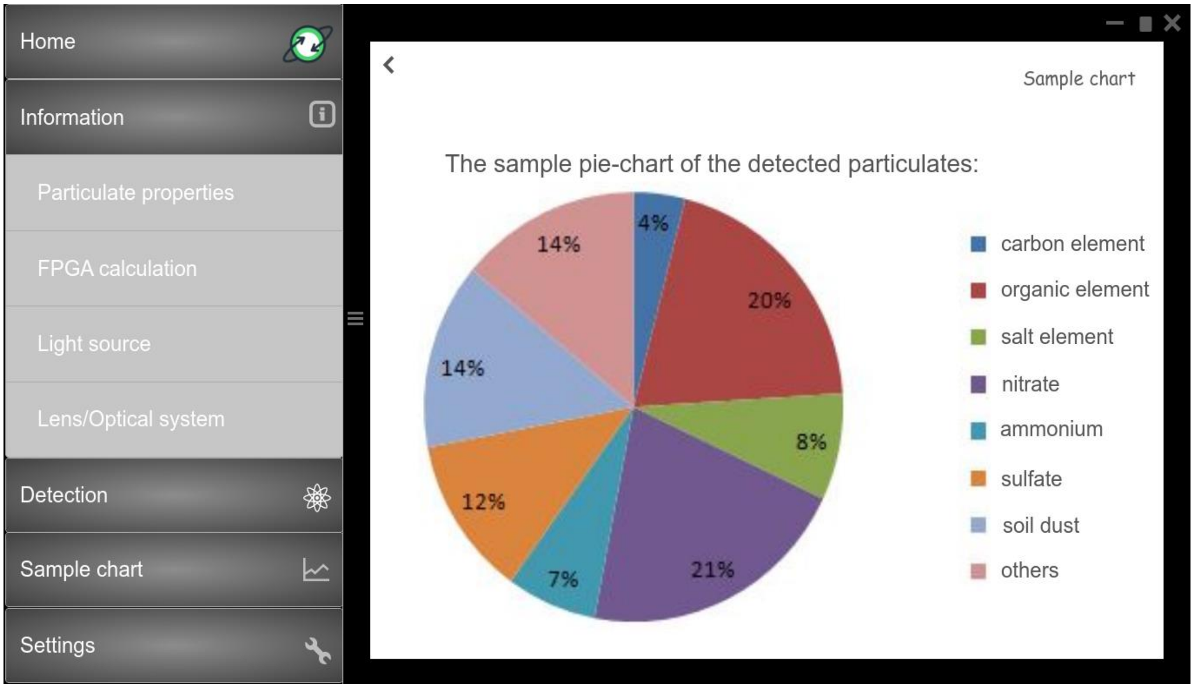

Figure 34: Sample pie-chart of detected particulates

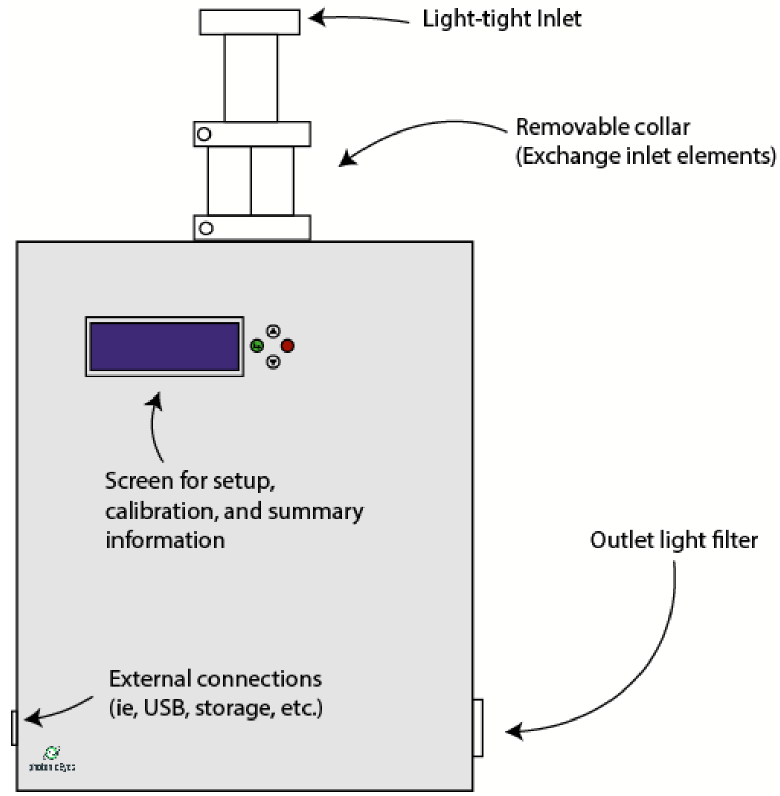

Figure 35: External appearance of SpecTro

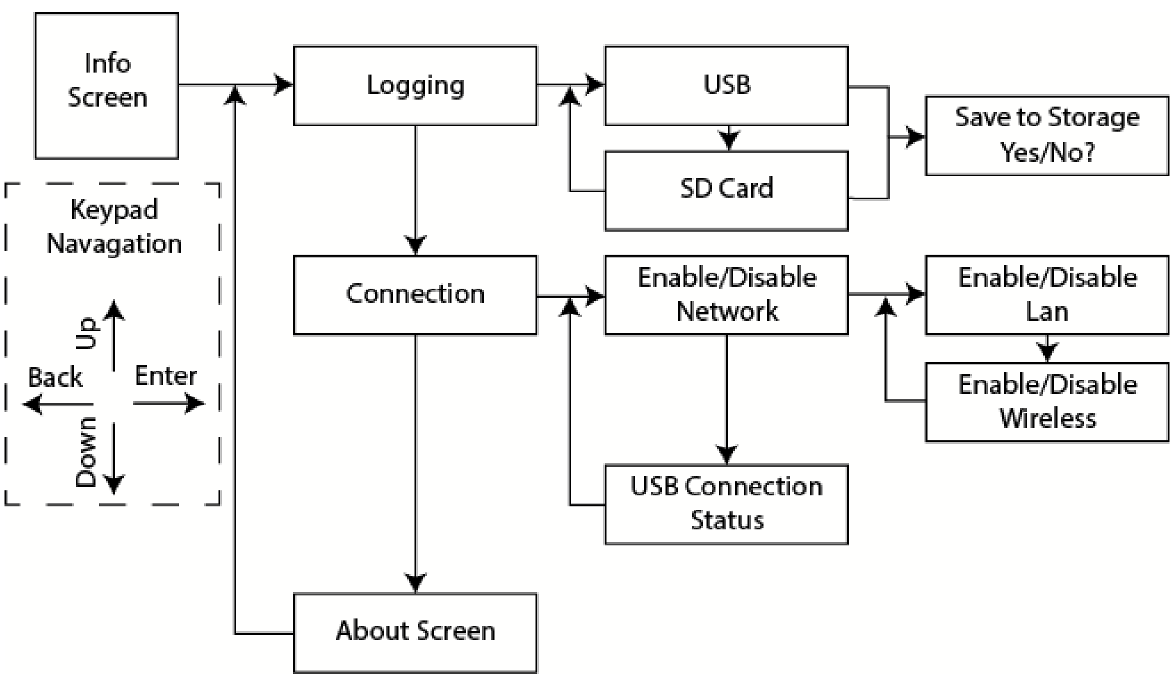

Figure 36: Navigation of the external 16x2 LCD screen

Conclusion

The User Interface design requirements plays a significant role in having the product accepted by users. During the implementation phase, it is important to keep in mind that many users may not have the same technical skills as others, thus the interface should be designed such that it is easy and straight-forward for our target audience. This report summarizes how we were able to identify the key qualities and components necessary for an intuitive interface design based on Don Norman's Seven elements of UI Interaction. Our goal is to create an intuitive and easy-to-use display while delivering useful and simple results for our prototype demo. We aim to provide quality products with an innovative design held to the highest of standards with careful planning and attention to detail.

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