4-26-2024

Spectrophotometric Device for Early Malaria Detection

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Loyola Marymount University
University Honors Program

Spectrophotometric Device for Early Malaria Detection

A thesis submitted in partial satisfaction

of the requirements of the University Honors Program

of Loyola Marymount University

by

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26 April 2024

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Senior Project 2023-2024

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Abstract

Malaria remains a significant global health challenge, with millions of cases reported annually, particularly in resource-limited regions. Timely and accurate diagnosis is crucial for effective treatment and disease management. Unfortunately, there are still significant challenges in existing testing procedures, which are often expensive, inaccurate, or impractical for mass testing. While spectrophotometry has been proposed as a detection tool for other tropical diseases such as dengue fever, no prototype has been made for any disease, including malaria. This report addresses this gap by presenting a spectrophotometric-based malaria detection tool that achieves high sensitivity at a low cost. The inclusion of a user-friendly interface ensures simplicity in its operation, making it suitable for deployment in field settings.

Contents

1 Introduction

Malaria affects over 40% of the world's population, and its impact is starkly evident in the 619,000 lives claimed by the disease in 2021 [1],[2]. The primary mode of transmission occurs through asymptomatic cases, which often go undetected due to limitations in existing malaria testing technologies that predominantly focus on symptomatic cases [3].

Current state-of-the-art solutions for malaria diagnosis primarily involve two categories: microscopic smear tests and antigen tests [4]. Microscopic smear tests, considered the gold standard, rely on expensive equipment and skilled technicians, making them inaccessible in resource-limited regions where the disease is most prevalent. In contrast, antigen tests, while more cost-effective and suitable for such settings, fall short in detecting asymptomatic cases with lower parasite concentrations [5]. This trade-off between accuracy and accessibility underscores the need for innovative solutions.

Spectroscopy-based diagnostic methods have emerged as a promising avenue in laboratory settings. However, these methods face challenges in transitioning from controlled laboratory conditions to real-world applications, especially in resource-constrained settings. The lack of validation, high costs, and limited user-friendliness remain significant drawbacks to the widespread adoption of these spectroscopy-based solutions.

Therefore, there exists a need for a portable, cost-effective, and user-friendly solution that seeks to bridge the accessibility and accuracy divide that currently exists in the malaria diagnostic field.

2 Project Objective

2.1 Background Information

Malaria is a significant global health issue primarily affecting tropical and subtropical regions of the world. Over 40% of the world's population, roughly 247 million people, are at high risk of contracting malaria. This resulted in 619,000 global deaths in 2021, most of which were children in sub-Saharan Africa [1],[2]. The primary mode of transmission occurs through asymptomatic cases that remain undetected because of current limitations with malaria testing technology which currently focuses on testing symptomatic cases [3].

Currently, conventional malaria testing devices and methods fall into two categories: microscopic smear tests and antigen tests [4]. Microscopic smear tests use microscopes to examine a drop of the patient's blood. These tests are considered the gold standard for malaria diagnosis. Unfortunately, many of the world's most affected areas lack sufficient resources to administer microscopic smear tests. A widely used alternative is antigen rapid diagnostic tests (RDTs) which can provide results in 2 to 15 minutes for a fraction of the cost of most laboratory

methods. These types of tests find their primary utility in resource-limited areas. However, they are inadequate for detecting asymptomatic cases of malaria when parasite concentrations are lower [5]. Most portable RDTs use antigen detection to test for one of two dominant strains of malaria: falciparum (Pf) or non-falciparum (Pv). Pf is more severe, making it responsible for more deaths while Pv is more common, making it responsible for most of the asymptomatic cases. A list of the most prominent RDTs in field use is shown in Table 1 with a short description of their functionality, use cases, false positive rate, and price.

Table 1: Most prominent RDTs

Device	Description	Use Case	False Positive Rate (%)	Cost ($)
SD Bioline Malaria Ag Pf/Pan	Detects antigens for Pf and Pv strains	Used where Pf and Pan strains are common	2.2 - 12.5 [6],[7]	0.70
Care Start Malaria RDT	Detects antigens for Pf, vivax, and mixed infections	Used where Pf and Pan strains are common	6.5 [8]	4.90
Paracheck Pf	Detects antigens for Pf	Used where Pf strains are common	<9 [9]	1.00
First Response Malaria Ag Combo (PLDH/HRP2)	Detects the pLDH and HRP2 antigens	Used for comprehensive screenings	5 [10]	2.75

There have been several studies that have demonstrated the potential use of spectroscopy for malaria diagnosis in a laboratory setting. One study found that mid-infrared spectroscopy paired with machine learning techniques could be used to detect malaria in human dried blood spots; however additional field validation and improvement in classification algorithms were necessary before the approach could be used [11]. Another such study was able to illustrate that Attenuated Total Reflection-Fourier transform infrared spectroscopy has the potential to be developed into an efficient and reliable malaria diagnostic tool [12]. This study also incorporated the use of a Cloud-based system to analyze the data collected. Additionally, another study analyzed the use of spectrophotometry, a type of absorption spectrometry, to detect hemozoin (HZ), a pigment found in malaria [13]. This study was able to demonstrate a proof of concept for the detection of malaria in whole blood using spectrophotometry. In short, many studies have demonstrated a proof of concept for a spectroscopy-based malaria diagnosis device; however, there has not been any validation in using these techniques under real-world conditions at an affordable cost.

As of 2023, only one spectroscopy-based diagnostic device has been proposed by a research team at Johns Hopkins [5]. The device combines label-free Raman spectroscopy and diffuse reflectance spectroscopy to detect parasites and genetic diseases such as sickle cell disease. Despite this, no research on this method has been published and its viability has not been proven. Therefore, there is a need to develop an affordable, portable, and user-friendly device that can be used to rapidly and accurately diagnose malaria in its infancy. The solution being proposed in this report is a Spectroscopy-based Portable Equipment for Comprehensive Malaria Testing and Analysis (SPECTRA) which uses spectrophotometry to detect HZ in a sample.

The motivation for this solution comes directly from the definition of "ethical thory" according to the Electrical and Computer engineering department at Loyola Marymount University [21]. Saying "morals are universal principles, laws, or rules that are generally accepted as good," SPECTRA was designed with the moral principle in mind that no child or human should go without proper healthcare due to lack of access.

2.2 Customer Requirements

The proposed SPECTRA device should fulfill the following requirements. First, it should be no larger than 1 ft^3 and no heavier than 10 lb to ensure its portability. The device should also cost less than $300 to manufacture and construct to ensure its affordability. Additionally, this device must be sensitive enough to accurately detect malaria when it is in its Trophozoite stage. This is because, during this stage of the parasite's life cycle, the infection is still asymptomatic and undetectable by many malaria diagnostic devices [14]. Lastly, the SPECTRA device should have an automated interface to be as user-friendly as possible. A more general list of customer requirements is shown below.

1. The system shall detect malaria in its Trophozoite stage.
2. The system shall be portable.
3. The system shall have a low cost.
4. The system shall be user-friendly.

3 Proposed Solution

3.1 Trades Leading to Proposed Solution

The concept table for this project is shown in Table 2. The table headings identify the main elements and functions to be achieved in the design, and the entries in each corresponding column display potential solutions to those functions. Table 2 examines different options for user interface, display, light source, mount, light detector, and channel. The potential solution is identified by the combination of underlined items. The concept fan, shown in Figure 1, is a graphical representation of the concept table and helps to show how this project fits into the

wider issue that it aims to solve. The concept table and concept fan were completed during the fall semester. Since then, the design of SPECTRA has changed. Instead of using the light source, mount, and channel as indicated in Table 2, SPECTRA now uses a white LED for the light source, a cuvette for the mount, and no longer uses an optical fiber cable.

Table 2: Concept table for SPECTRA

User Interface	**Display**	**Light Source**	**Mount**	**Light Detector**	**Channel**
Buttons	LCD	High power deep red LED	Acoustic levitation	Photodiode	Optical fiber cable
Touchpad	LEDs	Laser	PDMS well	Phototransistor	
		LED Array			

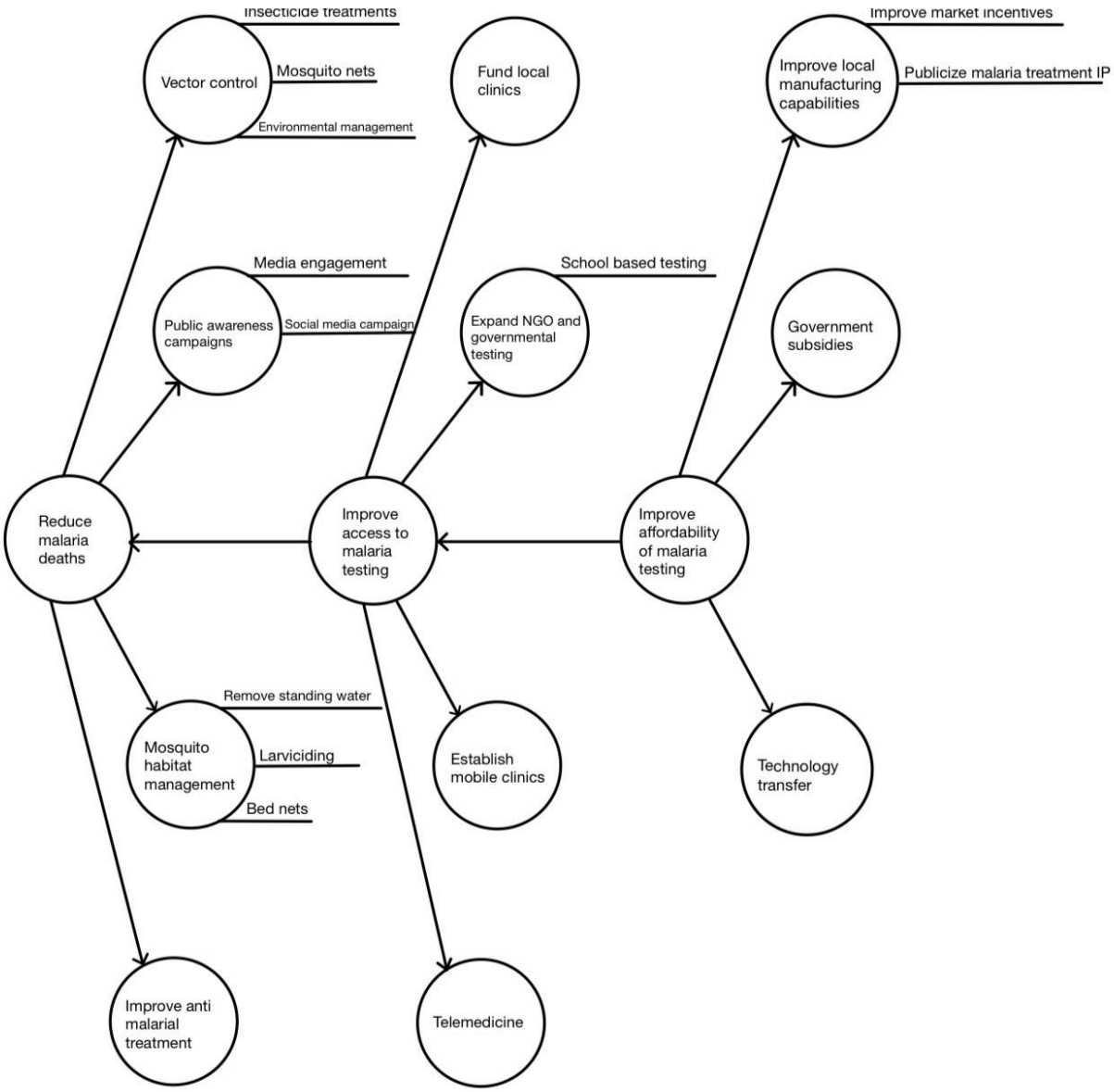


Figure 1: Concept fan for SPECTRA design decisions and choices

Tables 3 and 4 show the decision matrices for the major parts of SPECTRA: the light detector and the light source, respectively. The matrix provides quantitative reasoning for why one design choice may be better than another.

Tables 3a and 4a show how the weight values of the specified selection criteria were chosen for the light detector and the light source, respectively. In these tables, each criterion was systematically compared to all others. For example, in the first row of Table 3a, the cost of the light detector is compared to itself, accuracy, spectrum, and implementation. Each criterion was judged on its importance compared to the rest of the criteria on a scale from 1 to 9, 1 being equally as important and 9 being extremely more important. For example, in the second row of

Table 3a, accuracy was deemed to be moderately more important than cost, so it was assigned a score of 3; therefore, in the first row of the table, the cost was given the reciprocal value of ⅓ when compared to accuracy. Then, the geometric mean for the criteria was calculated which was then used to normalize the weights for each criterion. This was done to reduce any bias in the data.

Tables 3b and 4b show the comparison between the specified selection criteria, in the rows, and the possible solutions, in the columns. The weights for each possible solution were calculated in the same way as the weights for the criteria shown in Tables 3a and 4a. However, rather than using a qualitative scale from 1 to 9, the weights were determined based on quantitative data based on the criterion of each possible solution. Then, the score for each possible solution was calculated by multiplying the weight of the selection criterion by the weight of the possible solution and summing the values in each column. As shown in Table 3b, the photodiode has a higher score making it a better choice for SPECTRA. Table 4b shows the deep red LED to be the best choice for the light source. Again, since the fall semester, the design for SPECTRA changed and now uses a white LED.

Table 3a: Pairwise comparison matrix for the light detector

	Cost	**Accuracy**	**Spectrum**	**Implementation**	**Geometric Mean**	**Weights**
Cost	1	1/3	1/7	1/3	0.4	0.08
Accuracy	3	1	1/5	1/2	0.7	0.14
Spectrum	7	5	1	1	2.4	0.47
Implementation	4	2	1	1	1.6	0.31

Table 3b: Decision matrix for the light detector

Criteria	Weight	**Photodiode**	**Phototransistor**	**Photomultiplier Tube**
Cost	0.08	.6	.33	.07
Accuracy	0.14	0.1	0.15	.75
Spectrum	0.47	0.33	0.33	.33
Implemen-tation	0.31	0.45	0.45	0.1
Score		0.36	0.34	0.30

Table 4a: Pairwise comparison matrix for the light source

	Cost	**Power**	**Spectrum**	**Geometric Mean**	**Weights**
Cost	1	3	1/7	0.8	0.2
Power	1/3	1	1/6	0.4	0.1
Spectrum	7	6	1	3.5	0.7

Table 4b: Decision matrix for the light source

Criteria	Weight	**Deep Red LED**	**Laser**	**LED Array**
Cost	.2	0.76	0.01	0.23
Power	.1	0.007	0.002	0.991
Spectrum	.7	0.4	0.4	0.2
Score		0.43	0.28	0.29

Tables 5 and 6 show the Pugh concept selection method for the light detector and the light source, respectively. The Pugh tables compare specific concepts, shown in the columns, against selection criteria, shown in the rows. Each criterion was determined to have a weight of 1-5 depending on its importance, with 1 being least important and 5 being most important. Then, the concept that was initially believed to be the best was chosen to be the baseline concept. All other concepts were compared to the baseline and given a weight of +1 if they were better, 0 if they were equal, and -1 if they were worse. The score for each concept was determined by multiplying the criterion weight by the corresponding concept weight and summing the column.

From Table 5, the photodiode was determined to be the best option for the light detector, and from Table 6, the deep red LED was determined to be the best option for the light source.

Table 5: Pugh concept selection for the light detector

Criteria	Weight	**Photodiode (Reference)**	**Phototransistor**	**Photomultiplier**
Accuracy	4	-	-1	+1
Cost	3	-	+1	-1
Spectrum	5	-	0	0
Implementation	3	-	0	-1
Score		-	-1	-2
Continue?		Yes	No	No

Table 6: Pugh concept selection for the light source

Criteria	Weight	**Deep Red LED (Reference)**	**Laser**	**LED Array**
Cost	4	-	-1	-1
Power	3	-	-1	+1
Spectrum	5	-	0	-1
Score		-	-7	-6
Continue?		Yes	No	No

Table 7 shows the SCAMPER idea generation process for SPECTRA. The SCAMPER method is a creative thinking technique that encourages innovative problem-solving by reimagining and reconfiguring various aspects of an idea to spark fresh insights and creativity.

Table 7: SCAMPER generation process for SPECTRA

Substitute	SPECTRA substitutes costly and technically difficult optical methods of malaria detection with spectrophotometry.
Combine	SPECTRA combines a spectrophotometry-based malaria detector with a user interface that makes it simple to use by any person regardless of technical experience.
Adapt	SPECTRA adapts the technology found in other handheld spectrophotometers which have a much broader use case causing them to be significantly more expensive. By focusing on detecting malaria, SPECTRA reduces the complexity and cost of those other devices.
Modify	SPECTRA modifies the design of a handheld spectrophotometer by utilizing smaller low-power LEDs to create a portable version of the system. A sensor and an Arduino replace the spectrometer from the original design.
Put to another use	SPECTRA could be modified to detect other diseases, parasites, or toxins. A particular field of interest could be microplastics or lead detection in blood.
Eliminate	Eliminating the need for a blood sample could make SPECTRA even better by not requiring invasive measures. Component-wise, LEDs would have to be replaced with a laser in order to have a power high enough to detect beneath the skin's surface.
Reverse	The SPECTRA process cannot be rearranged.

3.2 Technical Requirements

Table 8, shown below, demonstrates the requirements specifications for the proposed SPECTRA prototype. The engineering requirements for this project were determined based on the customer requirements that were previously described. The SPECTRA prototype is required to be sensitive enough to detect HZ at a concentration of 0.35 g/L. This is because when HZ is present in blood at that concentration, the malaria parasite is still in its infancy. In this stage of its life cycle, typical RDTs are not able to reliably detect malaria. It should be noted that because HZ is relatively unstable and hard to test with, Dr. Kevin Njabo, director of the Center for Tropical Disease Research at UCLA recommended using chlorophyll as a substitute for HZ as they have similar absorption spectra. The device should also be compact and lightweight so that it can be

easily transported by traveling nurses, clinics, nonprofit organizations, and infectious disease experts. Additionally, the proposed SPECTRA device should have a user-friendly interface that automates most aspects of the malaria-testing process. This is crucial because the administration of dependable and precise malaria detection tests typically demands the expertise of well-trained specialists, a resource that the target demographic may not always have. Lastly, the SPECTRA device should be cost-effective to ensure its accessibility and affordability for a broader range of users, particularly in regions with limited resources where the prevalence of malaria is often higher.

Table 8: General requirements analysis framework for SPECTRA prototype

Marketing Requirements	**Engineering Requirements**	**Justification**
1	1. Should be sensitive enough to detect HZ at a concentration of at least 0.35 g/L.	This is the concentration at which malaria is in its Trophozoite stage.
2	2. Should be no larger than 1 ft^3.	This ensures the portability of the device.
2	3. Should be no heavier than 10 lbs.	This ensures the probability of the device.
4	4. Should have a user-friendly interface with no more than 4 buttons.	Intensive training requires resources the target demographic does not have.
1-4	5. Production cost should not exceed $300.	Device is targeted towards clinics in underdeveloped nations.
Marketing Requirements: 1. The system shall detect malaria in its Trophozoite stage. 2. The system shall be portable. 3. The system shall have a low cost. 4. The system shall be user-friendly.		

Figure 2, shown below, contains the marketing requirements, engineering requirements, engineering-marketing tradeoffs, engineering tradeoffs, and the target values for the engineering requirements for SPECTRA. For example, as seen in Figure 2, there is a strong, positive correlation between user-friendliness and the user interface, meaning that the more extensive the user interface is the more user-friendly the SPECTRA prototype becomes. The figure also shows that accuracy and production cost have a strong, positive correlation, meaning that as the production cost decreases, so does the accuracy. Additionally, it can be seen that within the

engineering requirements, there is a directly proportional relationship between the size and weight of the proposed device.

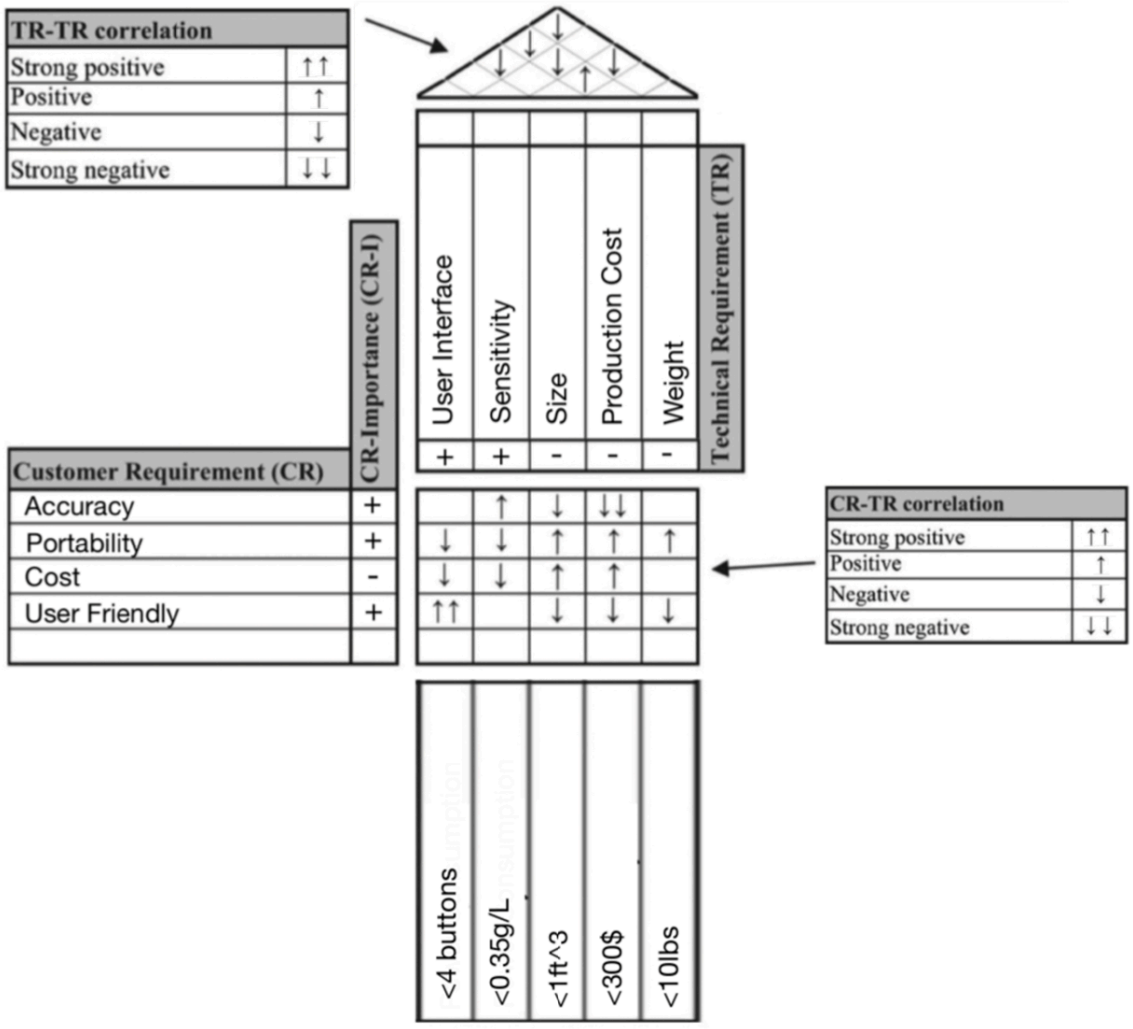


Figure 2: House of quality for SPECTRA prototype

The competitive benchmarks for malaria-detecting devices are shown in Table 9. Each RDT is compared based on the engineering requirements for SPECTRA. Because no spectroscopy-based RDT currently exists on the market, the table compares SPECTRA to the most widely used antigen tests on the market. Antigen tests are evaluated differently than other RDTs because their effectiveness is based on their sensitivity to the volume of parasites in a quantity of blood [6]-[9]. Each of the values for sensitivity were measured at a volume of 100 parasites per μL of blood.

Table 9: Competitive benchmarks for malaria-detecting devices

	SD Bioline Malaria Ag Pf/Pan	**Care Start Malaria RDT**	**Paracheck Pf**	**First Response Malaria Ag Combo (PLDH/HRP 2)**	**Our Design**
User Interface	N/A	N/A	N/A	N/A	Yes
Sensitivity (%)	<91.7	<90.77	<98.2	<93	~98
Size (ft^3)	-	-	-	-	<1
Weight (oz)	2.89	2.89	2.34	-	<160
Cost ($)	0.70	4.90	1.00	2.75	<300

3.3 System Description

Functional decomposition was applied to this project to decompose the system into smaller subsystems in order to facilitate the design and assembly of SPECTRA. Figure 3 shows the highest level (Level 0) of system functionality which describes the functional requirement for the whole system.

Figure 3: Level 0 SPECTRA functionality

Table 10 details the functional requirements displayed in Figure 3. The two inputs to the system are the blood sample and a user-controlled interaction to start running a test. The output of the system is a message that informs the user if there was hemozoin detected in the blood sample.

Table 10: Level 0 SPECTRA functionality

Module	**SPECTRA**
Inputs	• Blood sample • User-controlled run test stimulus
Outputs	• Result message stating whether or not hemozoin was detected.
Functionality	• Use absorption spectroscopy to detect if a blood sample has hemozoin in it.

The Level 1 design for this system is shown in Figure 4. This is the main design architecture of the system, showing the organization between the different modules of SPECTRA. To put it simply, the system will consist of a microprocessor, light source, channel, light detector, and battery. The first stage, the microprocessor, will receive a user input, signaling it to start running a test. The light source will receive a voltage signal from the microprocessor, causing it to turn on and send a beam of light through the optic fiber channel. This will pass through the blood sample, and the light detector will measure the light spectrum after it has passed through the blood sample. Lastly, the microprocessor will process the data and display a message to the user specifying if hemozoin was detected.

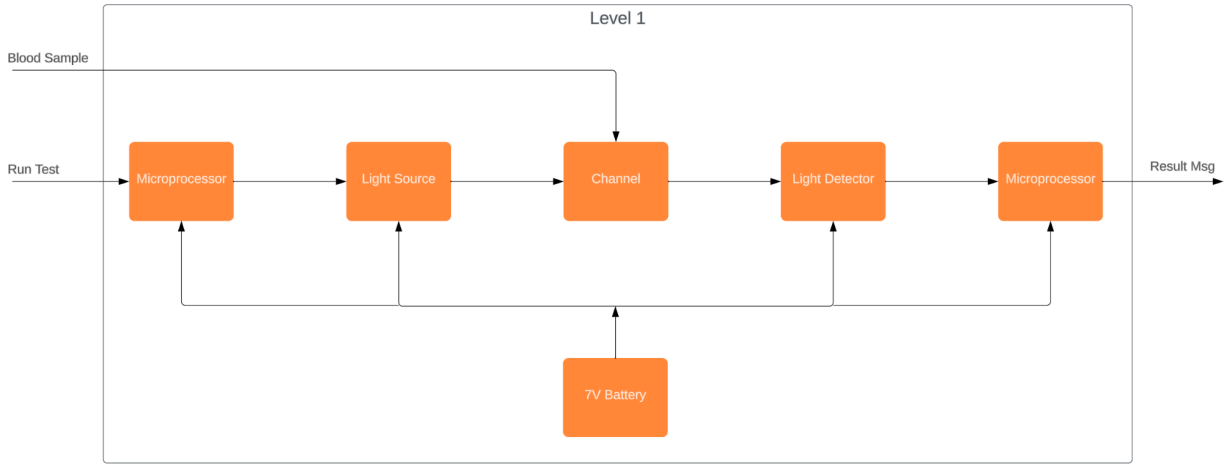


Figure 4: Level 1 SPECTRA functionality

Table 11 shows the functional requirements for the microprocessor subsystem from Figure 4. Because SPECTRA will be a portable device, it shall be powered by a 7V battery. Additionally, the microprocessor will take a user response and the spectrum data from the light detector as inputs. It will output a result message to the user as well as a 5V signal to power the light source and light detector.

Table 11: Level 1 microprocessor functionality

Module	**Microprocessor**
Inputs	● 7V Battery ● Spectrum data from the light detector ● User-controlled run test stimulus
Outputs	● 5V signal to the light source and light detector ● Result message
Functionality	● Provides power for the light source and light detector. It also runs the user interface, processes the spectrum data collected from the light detector, and outputs a result message.

The functional requirements for the light source subsystem are shown in Table 12. The light source will have two inputs: the on signal from the microprocessor and the 5V from the Arduino Uno. The output of the light source will be light with a wavelength between 640 nm and 700 nm.

Table 12: Level 1 light source functionality

Module	**Light Source**
Inputs	● On Signal from the microprocessor ● 5V from Uno
Outputs	● Wavelength from 640-700 nm
Functionality	● Emits light at specific wavelengths to illuminate the sample

Table 13 shows the functional requirements for the channel. The channel will be used to direct the light from the light source to the blood sample to the light detector. The input will be the light from the light source, and the output will be the light to the light detector.

Table 13: Level 1 channel functionality

Module	**Channel**
Inputs	● Light from the light source
Outputs	● Signal to the light detector
Functionality	● Directs the light to the light detector, facilitating the analysis of the light by the sensor

Table 14 shows the functional requirements for the light detector subsystem shown in Figure 4. The two inputs to the subsystem are the light from the channel and the 5V signal being used to power the light detector. This subsystem will output the light spectrum data to the microprocessor for processing.

Table 14: Level 1 light detector functionality

Module	**Light Detector**
Inputs	● Light from channel ● 5V from Uno
Outputs	● Signal to the microprocessor
Functionality	● Measures the intensity of light after it has interacted with the sample

The general algorithm for the SPECTRA software is shown in Figure 5. Once the program is started, it will initialize all the variables and pins necessary for the device. Next, it will continue to check the light sensor until a button is pressed. If the button is pressed, then the microprocessor will send a signal to set the LED brightness, then the sensor will begin to read measurements. After processing the data, if absorption at a wavelength between 660 nm and 680 nm is detected, then a "Malaria Positive" message will be output by the device.

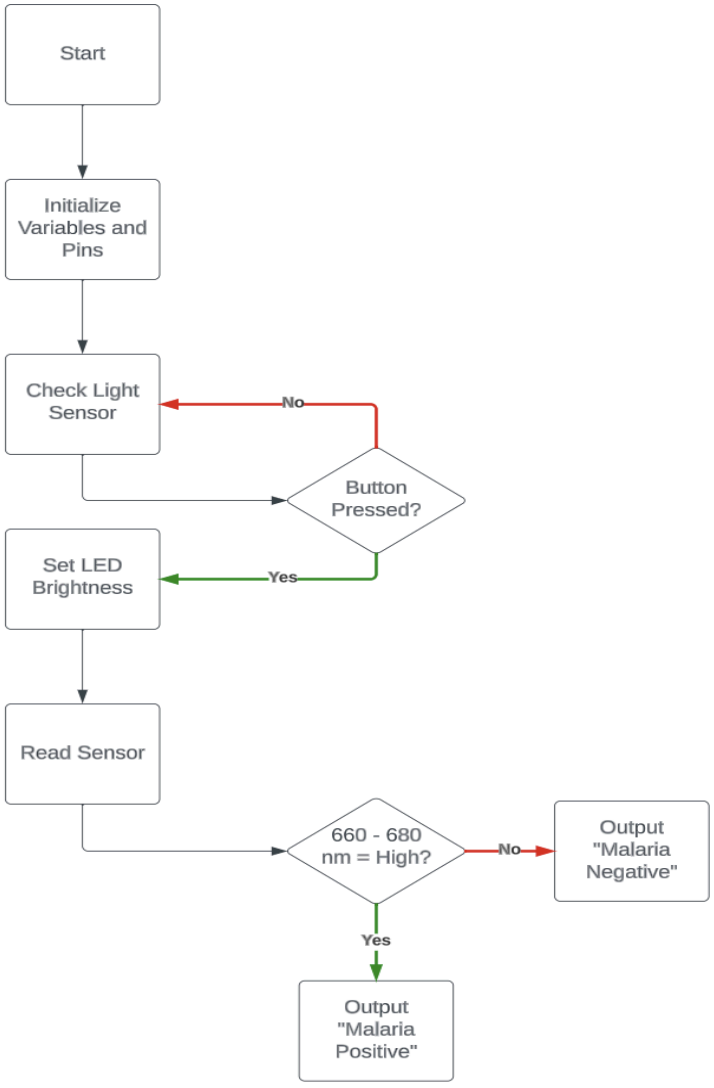


Figure 5: SPECTRA software algorithm

A work breakdown structure (WBS) was completed for SPECTRA to break down the hierarchical list of activities required to complete the project. The WBS is shown in Figure 6. The three main branches include building the SPECTRA electronics, building the SPECTRA encasement, and testing SPECTRA. Within the “SPECTRA electronics” branch, the three tasks that need to be completed are to design and build the portable spectrometer setup, determine the sample containment method, and create a user interface. Within the “SPECTRA encasement” branch, the two tasks that need to be completed are to implement the channel method and to create the SPECTRA housing. Lastly, within the “test SPECTRA” branch, the two tasks that will be completed are to test SPECTRA with a coffee ground sample and then with a blood sample.

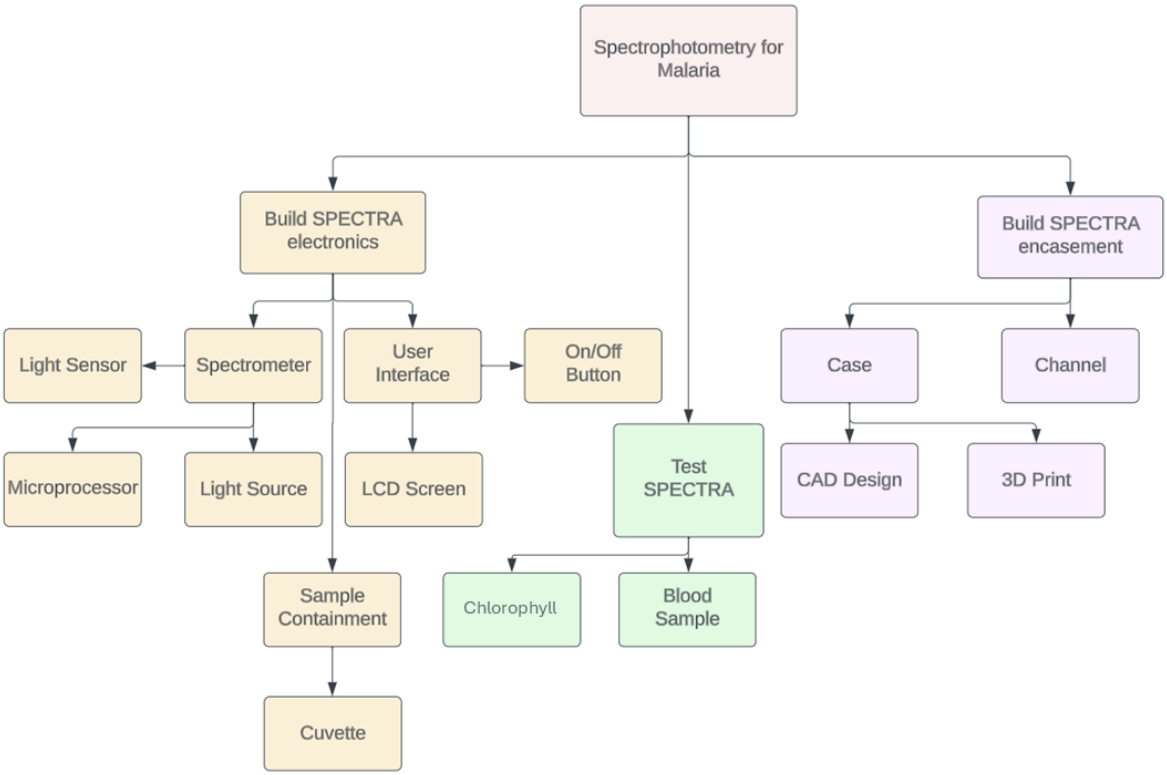


Figure 6: Work breakdown structure (WBS) for SPECTRA

3.4 Standards and Constraints

ISO standards are essential for the development of SPECTRA as they provide a framework to ensure the device's safety, effectiveness, and reliability. These standards help streamline the development process by offering guidelines for quality management, risk assessment, and safety considerations. Adherence to ISO constraints is crucial in meeting regulatory requirements, gaining market acceptance, and building trust among users and stakeholders. By following these standards, the development team can enhance the robustness of the device, minimize risks, and contribute to the overall success of the project.

Since ISO standards can be applied to all products, several were chosen that specifically pertain to medical devices. ISO 13485 focuses on quality management systems specific to medical devices, ensuring that the device is consistently produced and controlled to meet regulatory requirements. ISO 14971 addresses risk management, guiding the identification and mitigation of potential risks throughout the device's lifecycle. Electrical safety standards, such as IEC 60601-1 and IEC 61010-1, provide crucial guidelines for the safe design and operation of medical electrical equipment. FDA regulations and CE marking are essential for regulatory approval in the U.S. and European markets, respectively. Adhering to these standards will not only help meet regulatory obligations but also contribute to the device's overall quality, safety, and effectiveness.

3.5 Design Impact

This project is expected to bring about significant positive impacts in various fields, addressing critical challenges associated with malaria diagnosis and aligning with broader societal and ethical considerations.

The primary goal of SPECTRA is to improve malaria diagnosis by providing a portable, cost-effective, and user-friendly solution. In regions with limited healthcare resources, the affordability and accessibility of a reliable diagnostic tool can lead to early detection and prompt treatment, significantly reducing the risk of malaria in affected populations. Economically, this project provides a less expensive spectroscopy-based diagnostic tool compared to what is currently on the market.

The impact of SPECTRA extends beyond individual patients to contribute to global health initiatives. By focusing on malaria, a global health challenge, the project directly aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goal 3: Good Health and Well-being [15].

Unlike traditional, single-use malaria diagnostic methods which involve chemical reagents and extensive waste generation, SPECTRA employs spectrophotometry, minimizing the amount of waste used per test. Therefore, this project would contribute to a more sustainable way of malaria detection.

In implementing SPECTRA, the broader implications and potential risks associated with its deployment must be considered. This includes the potential for the device to misdiagnose an infected patient as healthy. While design considerations can mitigate the risk of false negatives, in a real life scenario, improperly maintained or constructed devices could have a much higher false negative rate. Annually in the US, 795,000 individuals are harmed from misdiagnosis [22]. These misdiagnoses could lead to undertreatment. Additionally, due to the hands-on nature of SPECTRA, a technician or nurse would be required to use this device. Should this device not

have proper health and safety standards in place, it could caue the infection of the user and further spread of malaria. To mititgate this, it has been shown that training for community health workers significantly reduces the likelihood of infection among those workers [23].

4 Electrical Design

4.1 Schematics and Circuit Diagrams

The following figures show the circuit diagram for each of the systems in the SPECTRA circuitry. Figure 7 shows the circuitry required for the LCD screen with I2C communication. Figure 8 shows the circuitry required to implement the button for the user to interact with. Figure 9 shows the circuitry required for the AS7341 sensor. Lastly, Figure 10 shows the circuit for the white LED.

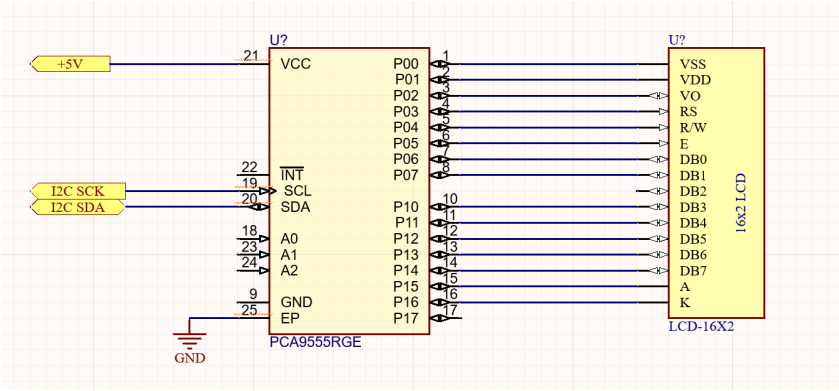


Figure 7: LCD circuit diagram

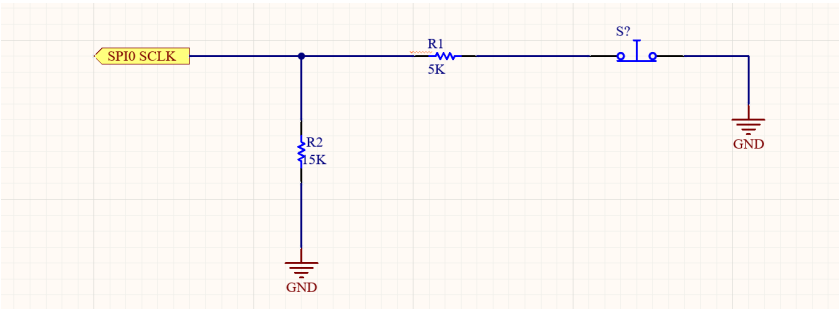


Figure 8: User interface push-button circuit diagram

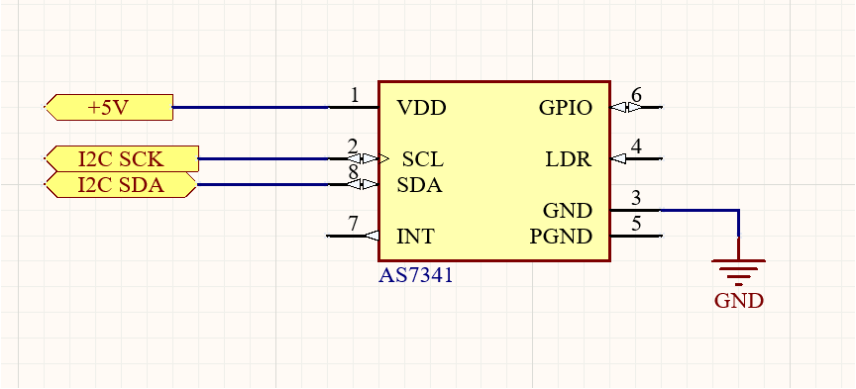


Figure 9: AS7341 sensor circuit diagram

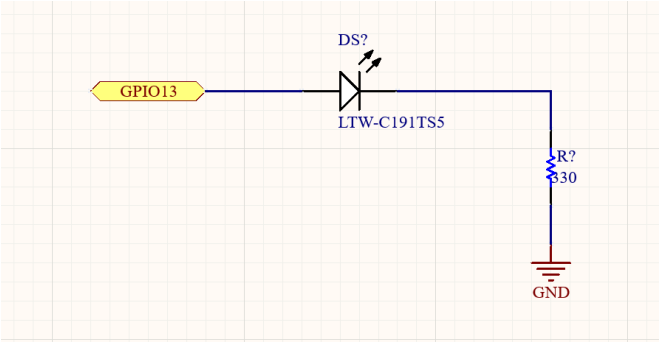


Figure 10: White LED circuit diagram

4.2 Wiring and Cable Diagram

Figure 11, seen below, shows the full SPECTRA system. It combines the LCD screen, push button, AS7341 sensor, and white LED, shown in Figures 7-10, respectively, along with a Raspberry Pi computer into a fully integrated system.

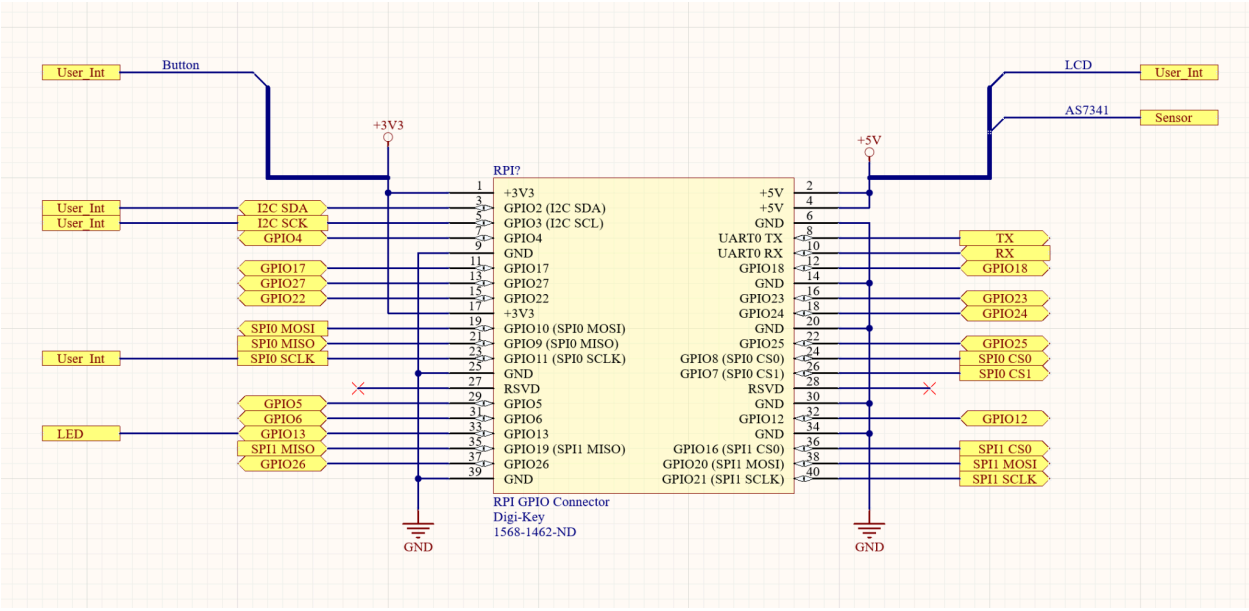


Figure 11: Fully integrated SPECTRA system

4.3 Bill of Materials

Table 15 shows the Bill of Materials for this project, listing all of the components and materials required to assemble SPECTRA. It should be noted that some of the components used were purchased, while some of the components used were provided by LMU. Only the components that were purchased were included in the cost estimate tables shown in section 4.6 of this report.

Table 15: Bill of Materials

Item	Part Name	Description	Purchased/ Provided	Quantity
1	AS7341	10-Channel Spectral Color Sensor	Purchased	1
2	White LED	5 mm white light LED	Provided	1
3	330 Ω Resistor	Current-limiting resistor	Provided	1
4	Raspberry Pi	Single-board computer for data processing	Purchased	1
5	LCD Screen	16x2 character LCD	Purchased	1
6	Push Button	Device for user interaction	Provided	1
7	PiJuice Hat	Raspberry Pi battery pack	Purchased	1
8	PCB protoboard	Prototyping board for soldering electronic components	Provided	1
9	Jumper wires	Wires for making connections between components	Provided	1 pack
10	Plastic cuvettes	For sample containment	Provided	1 pack
11	3D printing filament	Material for 3D printing housing	Purchased	1 roll

4.4 Mechanical Drawings

The mechanical drawing in Figure 12 illustrates the final Computer-Aided Design (CAD) model for the SPECTRA housing. This CAD model underwent many iterations until the final design was obtained. The housing was designed to meet the customer requirements shown in Table 8, ensuring compact dimensions of less than 1ft by 1ft by 1ft. Additionally, the design incorporates a front panel to include the simple user-interface, consisting of an LCD screen and two buttons. There are two main chambers in the housing: the Raspberry Pi compartment and the LED, cuvette, and sensor mounts. Figure 13 shows a detailed view of the mount for the LED, cuvette, and sensor. These CAD drawings were used to 3D print the housing and cuvette holder for SPECTRA.

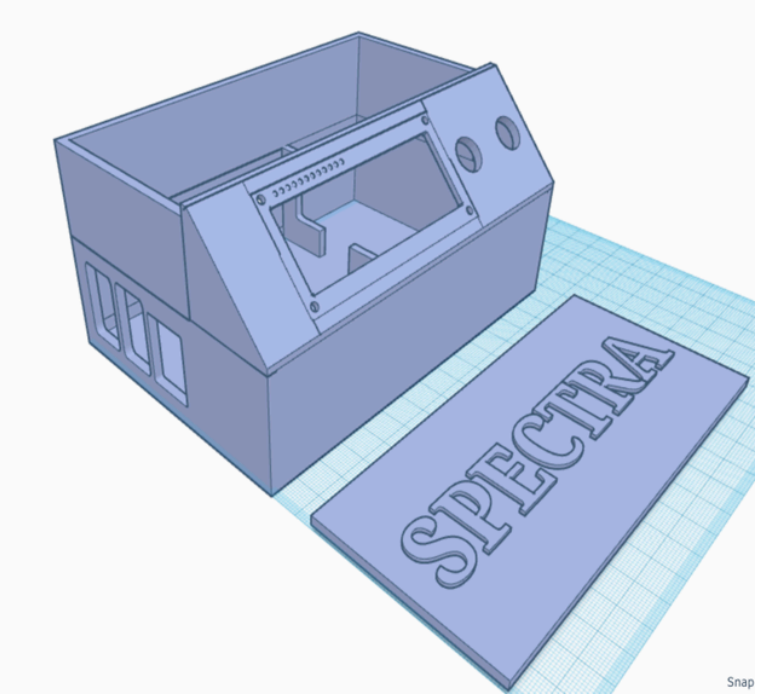


Figure 12: Final SPECTRA housing

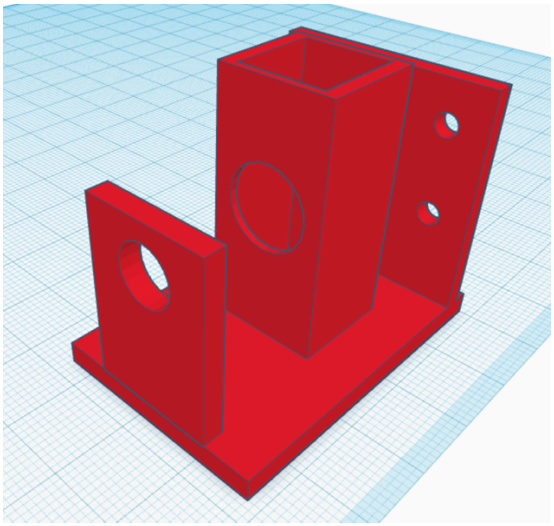


Figure 13: SPECTRA LED, cuvette, and sensor mount

4.5 System Design

Figure 14 describes the basic overview of the SPECTRA algorithm. Once the program is started, the device waits for a user to begin an experiment by pressing a button. Once the button is pressed, the device begins to calibrate the brightness of the LED. To do this, the AS7341 light sensor takes continuous light intensity measurements and SPECTRA reduces the duty cycle of the pulse-width-modulated signal powering the LED until none of the channels on the sensor are

saturating. Once the LED is correctly calibrated, the program prompts the user to place a cuvette with distilled water into SPECTRA to act as a reference solution for calibration, and the sensor takes a light intensity measurement. Then, the program prompts the user to remove the calibration solution and place the cuvette with the solution they desire to measure the absorbance of. The sensor then takes another light intensity measurement. Lastly, SPECTRA calculates the absorbance by taking the difference between the two measurements and determines whether or not "malaria", or in this case, chlorophyll, is detected.

Figure 14: SPECTRA algorithm overview

Figure 15, shown below, describes a more detailed overview of the algorithm used to determine whether or not chlorophyll is detected in a sample. Once started, the program waits for the user to place the calibration solution of distilled water. Then, the AS7341 sensor takes 5 light intensity measurements that are averaged together. Next, the program waits for the user to place the chlorophyll solution, and the AS7341 sensor takes 5 more light intensity measurements that

are averaged together. The program then takes the difference between the two averages and evaluates the result. If the result has a peak at a wavelength of 630 nm with an amplitude of at least 2000, a valley at 555 nm, and another peak at 445 nm, then the program outputs a “malaria detected” message. If any of the previous conditions are not satisfied the program outputs a “no malaria detected” message.

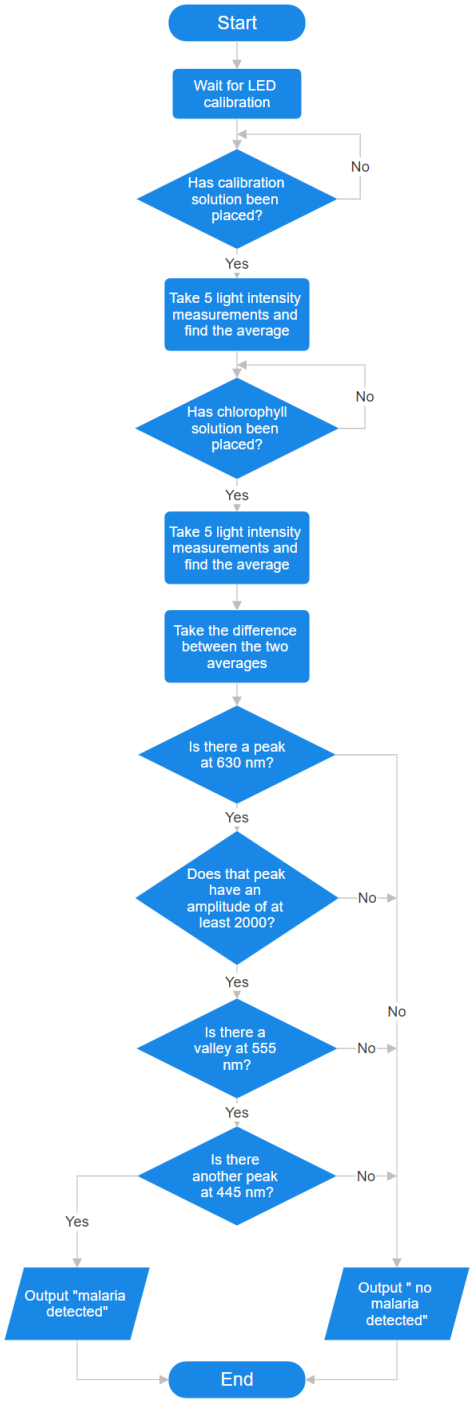


Figure 15: Detailed malaria detection algorithm

4.6 Cost Estimates

Table 16 shows the cost estimate for all the parts purchased throughout the duration of the project, including those that are not used in the current SPECTRA prototype. As shown in the table, the total amount of money spent on this project was $213.48, falling well within the $500 budget assigned at the beginning of the school year.

Table 16: Cost estimate for all purchased parts

Item No.	Item	Cost ($)
1	Deep Red LED	3.99
2	660 nm visible emitter	1.84
3	TSL2591 High Dynamic Range Digital Light Sensor	6.95
4	AS7341 Light (Spectrometer) Sensor	16.99
5	Photodiode 660nm	1.68
6	MT5720-IR 720nm IR emitter	7.20
7	Acoustic levitation device	13.79
8	Arduino Uno	27.60
9	PLA 3D printer filament	18.99
10	Raspberry Pi	35.00
11	16x2 I2C LCD screen	7.00
12	PiJuice Hat	71.50
13	4-pin JST PH connector	0.95
TOTAL		**213.48**

Table 17 shows the cost estimate for the final SPECTRA prototype, providing an overview of the anticipated expenses associated with manufacturing the device. The total estimated cost for manufacturing SPECTRA amounts to $165.91; however, it is important to clarify that the actual cost of the project was lower than the total indicated in Table 17 because some of the components listed in the table were provided by LMU. Table 18 shows the cost estimate of SPECTRA excluding the price of components that were provided by LMU.

Table 17: Cost estimate for the final SPECTRA prototype

Item No.	Item	Cost ($)
1	White LED	3.99
2	AS7341 light (spectrometer) sensor	16.99
3	PLA 3D printer filament	18.99
4	Raspberry Pi	35.00
5	16x2 I2C LCD screen	7.00
6	PiJuice hat	71.50
7	330 Ω resistor	0.06
8	Push button	2.50
9	PCB protoboard	1.50
10	Jumper wires	6.98
11	Plastic cuvette	0.45
12	4-pin JST PH connector	0.95
TOTAL		**165.91**

Table 18 shows the cost estimate for all of the components that were purchased and used in the current SPECTRA prototype. This table excludes the cost of the components that were provided by LMU, reducing the project's cost from $165.91 to $150.43.

Table 18: Cost estimate for the final SPECTRA prototype purchased components

Item No.	Item	Cost ($)
1	AS7341 Light (Spectrometer) Sensor	16.99
2	PLA 3D Printer Filament	18.99
3	Raspberry Pi	35.00
4	16x2 I2C LCD Screen	7.00
5	PiJuice Hat	71.50
6	4-pin JST PH connector	0.95
TOTAL		**150.43**

5 Experimental Test and Demonstration

5.1 Tests Used to Benchmark System Performance

Throughout the progression of this project, numerous tests have been conducted to assess the performance of SPECTRA, ensuring alignment with both customer and engineering requirements.

AS7341 Sensor Test:

The first test that was conducted was to test the measurement capabilities and accuracy of the AS7341 sensor. The experiment was designed to measure and compare the luminosity of three LEDs of different wavelengths using the red, 630 nm, sensor on the AS7341 breakout board. The three LEDs that were tested had wavelengths of 520 nm, 630 nm, and 670 nm. Each LED was placed 1 cm from the sensor and activated individually to record the corresponding luminosity data measured by the red sensor channel. The setup for this experiment can be seen in Figure 16. It was hypothesized that the 630 nm channel on the AS7341 breakout board would detect a higher intensity of light when measuring the 630 nm emitter as compared to the 520 nm and 670 nm emitters. The results of this test are shown in Figures 25-27 in the *Data Analytics* section of this report.

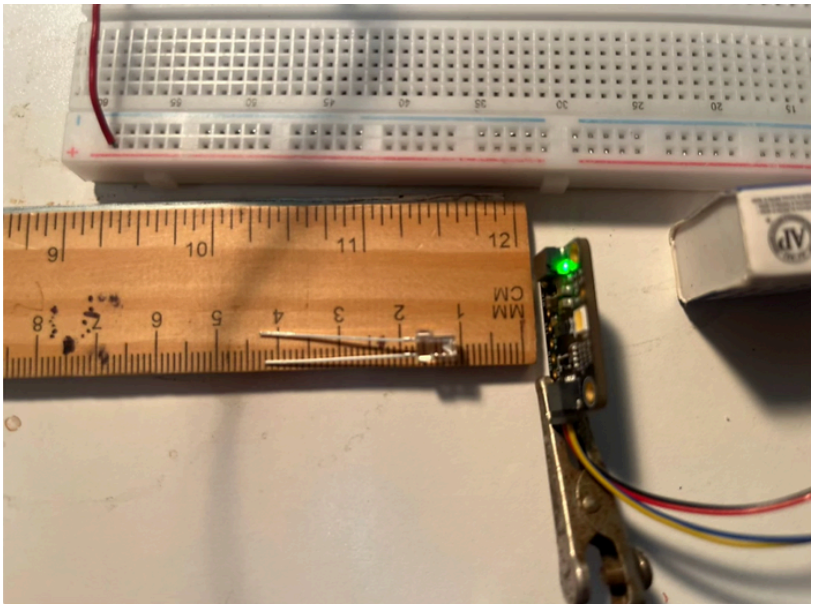


Figure 16: Experiment setup to test the red sensor

AS7341 Saturation Test with Potentiometer:

During the previously described test, an observation was made that the sensor was saturating; it was reaching the maximum digital value that it was able to record. Saturation is an issue because it limits the amount of absorbance data that a user can measure. This phenomenon can be related to the clipping that is seen when too large of a signal is input to an amplifier. Because the sensor was reaching the maximum value that it could read, it was essentially clipping the data and preventing the full absorption detected at a specific wavelength from being measured accurately. Therefore, the next two experiments that were conducted aimed at discovering the best ways to mitigate the saturation of the AS7341 sensor.

In the first of the two tests, a potentiometer was used to calibrate SPECTRA and vary the light intensity received by the sensor. The goal was to reduce the intensity of light from the LED until the sensor readings reached the point right below the saturation point. This would give the largest and most accurate range for measuring absorption. The resistance of the potentiometer was varied, starting at 200 Ω and ending at 1400 Ω, increasing by 200 Ω each trial for seven trials. For each trial, the light intensity was measured by the AS7341 sensor both with and without a chlorophyll sample between the LED and the sensor. The results from this experiment are shown in Table 19 in the *Data Analytics* section.

AS7341 Saturation Test with PWM:

In the subsequent test, SPECTRA was calibrated using pulse width modulation (PWM). Instead of varying the resistance in the circuit, as with the previous test, a constant 330 Ω resistor was

implemented and the duty cycle of the PWM signal was varied. The duty cycle began at 100% and was decreased by 20% for each trial. Light intensity measurements were taken by the sensor for each trial, both with and without the chlorophyll sample present. The results from this experiment are shown in Table 20 in the *Data Analytics* section.

Low Concentration Tests:

Once a dependable method for calibrating SPECTRA was established, the next steps involved confirming its accurate detection and precise measurement of a chlorophyll sample. Three different solutions were mixed using distilled water and chlorophyll. Each solution had a different concentration of chlorophyll: 2 g/L, 1 g/L, and 0.35 g/L. For this test, the first step was to measure the absorption spectrum of a chlorophyll solution using a spectrophotometer from LMU's chemistry department. This was done to generate an accurate baseline measurement of chlorophyll's absorption spectrum, essential for comparison with SPECTRA's readings to ensure their accuracy. Figure 17 shows the baseline absorption spectrum of chlorophyll measured with the spectrophotometer provided by the chemistry department.

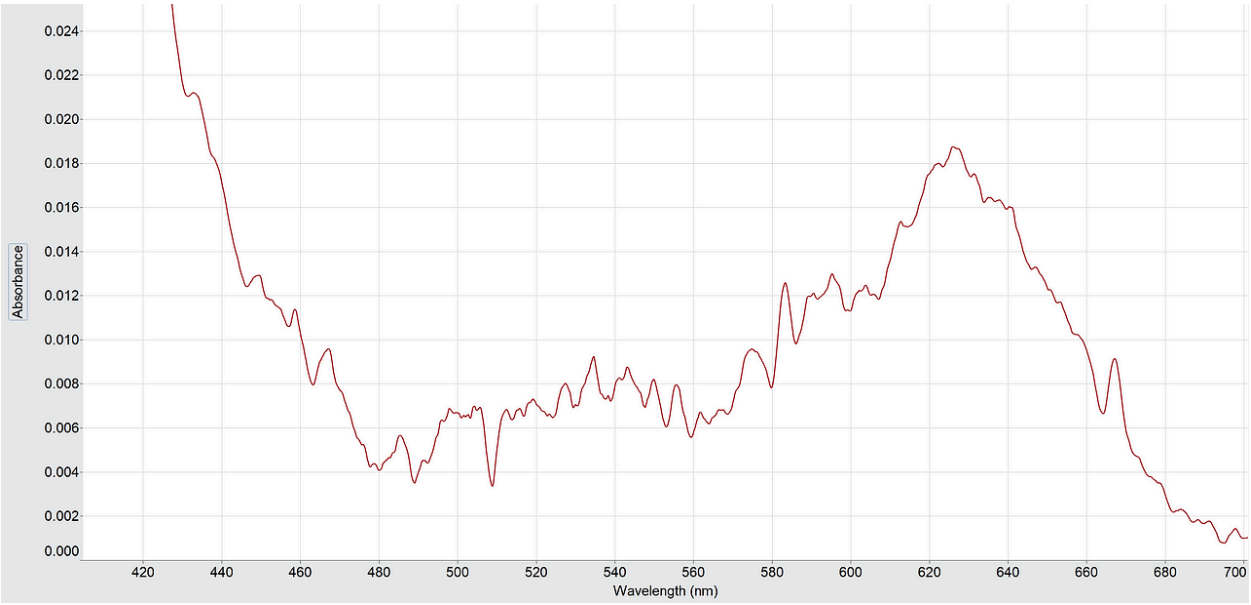


Figure 17: Absorption spectrum of chlorophyll

Before inputting each of the chlorophyll solutions to SPECTRA, the device was calibrated. This calibration involved reducing the duty cycle of the pulse-width-modulated (PWM) signal powering the LED in order to reduce its intensity until the AS7341 sensor was not saturating in any of its channels. Once SPECTRA was calibrated, a cuvette filled with distilled water was placed into the device and the sensor took light intensity measurements. Then, the 2 g/L solution was placed into the device and the sensor took light intensity measurements again. The absorbance was calculated by taking the difference between the two light intensity

measurements. The same process was followed for the 1 g/L solution and the 0.35 g/L solution. The results from these tests are shown in Figures 28-33 in the *Data Analytics* sections.

Chlorophyll vs. Dyed Solutions Test:

To assess SPECTRA's capability to differentiate chlorophyll solutions from other substances, an experiment was conducted. Four solutions of distinct colors were prepared for testing, initially planned to consist of food dye in distilled water. Due to unavailability, Blue Powerade, Red Powerade, and Orange Fanta were used instead. Additionally, a chlorophyll solution was included to verify SPECTRA's accuracy in distinguishing it from the other solutions. The same testing procedure as the previously described experiment was implemented. First, the absorption spectrum of each of the samples was measured using the spectrometer provided by the chemistry department, seen in Figures 34-36 in the *Data Analytics* section.

Then, a sample of distilled water was used to generate a baseline measurement for light intensity values before each of the testing solutions was placed into SPECTRA. Absorbance values measured by SPECTRA for each solution are depicted in Figure 37 in the *Data Analytics* section of this report.

Accuracy Rate:

Evaluating the true positive and false positive rates is crucial for gauging the performance and reliability of SPECTRA in accurately detecting target substances. A test was designed to determine both the device's ability to correctly identify the presence of chlorophyll (true positive rate) and its susceptibility to misidentifications (false positive rate). In evaluating the efficacy of SPECTRA, measurements were conducted to assess both the true positive and false positive rates. For the true positive rate, the absorption of a 0.35 g/L concentration chlorophyll sample was measured 20 times, and the output was recorded. The results are shown in Table 21 of the *Data Analytics* section.

5.2 Working Prototype

A prototype of the design was created and tested. The internal circuitry of SPECTRA, including the Raspberry Pi and the user interface, can be seen in Figure 18.

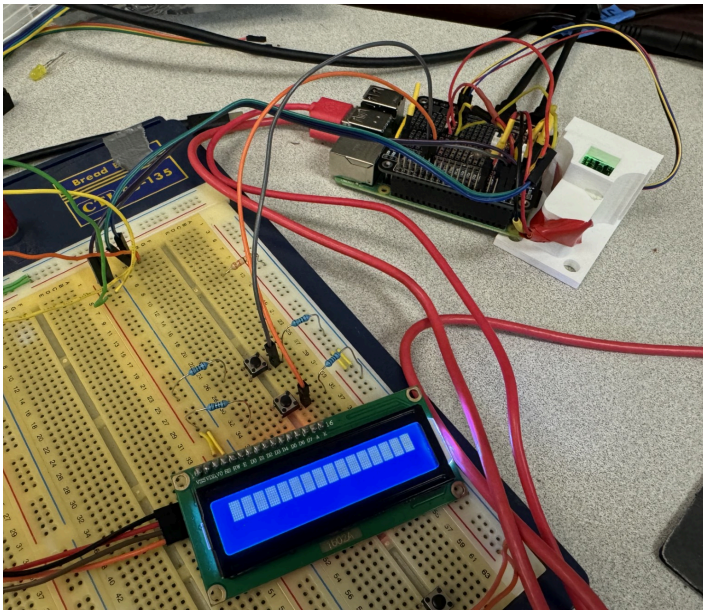


Figure 18: Internal circuitry of SPECTRA

Figure 19 gives a closer look at the SPECTRA electronics, displaying the LED and sensor mount, the cuvette holder, and the soldered PCB protoboard sitting on top of the Raspberry Pi.

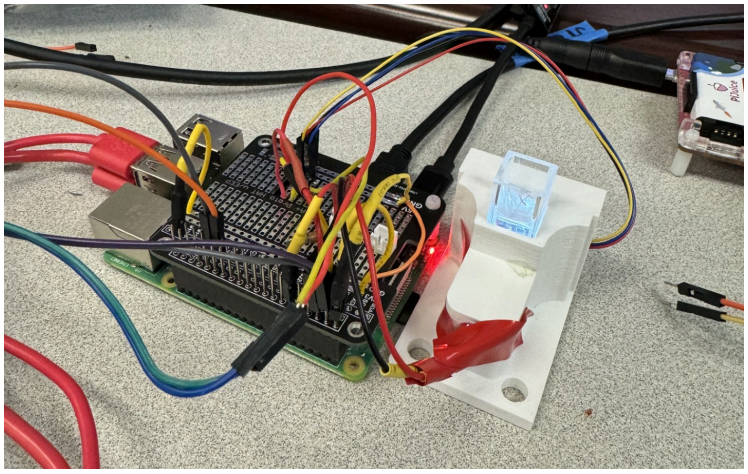


Figure 19: Close-up view of SPECTRA electronics

Figure 20 shows a front view of the final SPECTRA prototype with the lid of the encasement taken off. Figure 21 shows a top view of the final SPECTRA prototype with the lid off, illustrating the final, soldered PCB protoboard and the final iteration for the LED and sensor mount. Lastly, Figure 22 depicts a top view of SPECTRA with the lid of the encasement on.

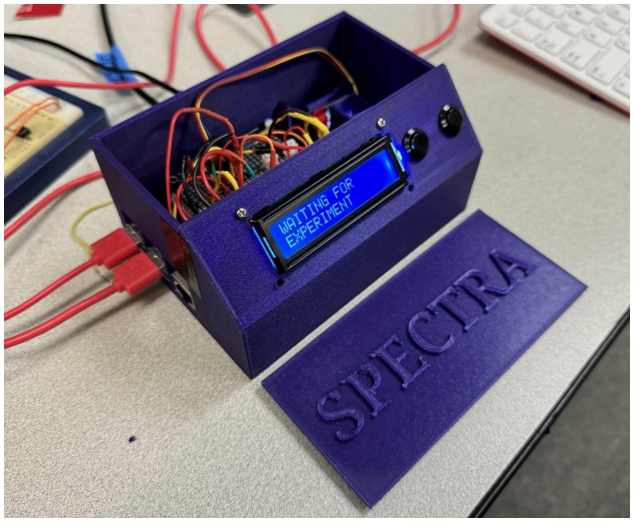


Figure 20: Front view of SPECTRA with the lid off

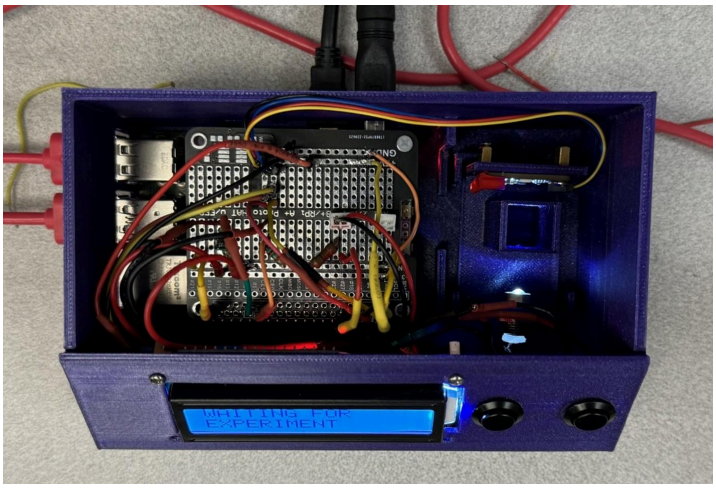
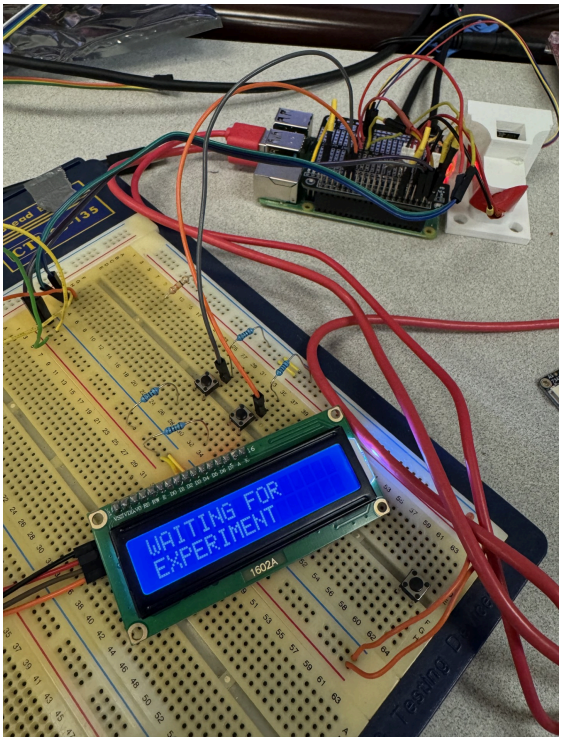


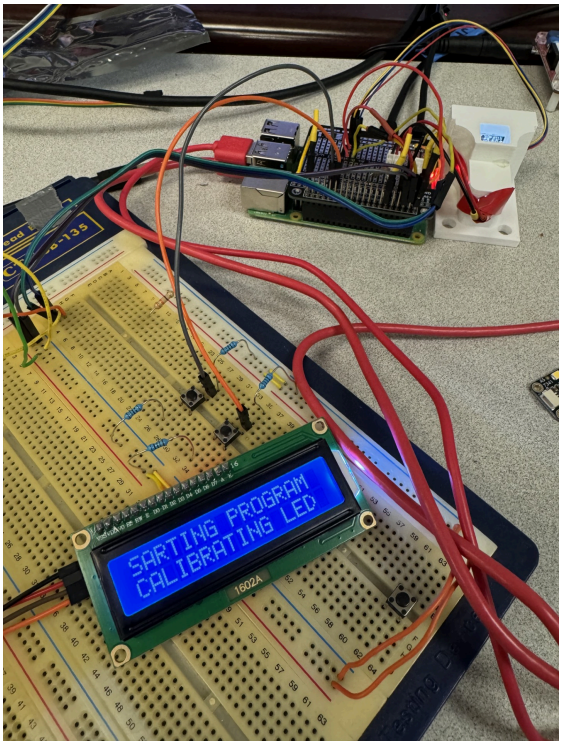
Figure 21: Top view of SPECTRA with the lid off

Figure 22: Top view of SPECTRA with the lid on

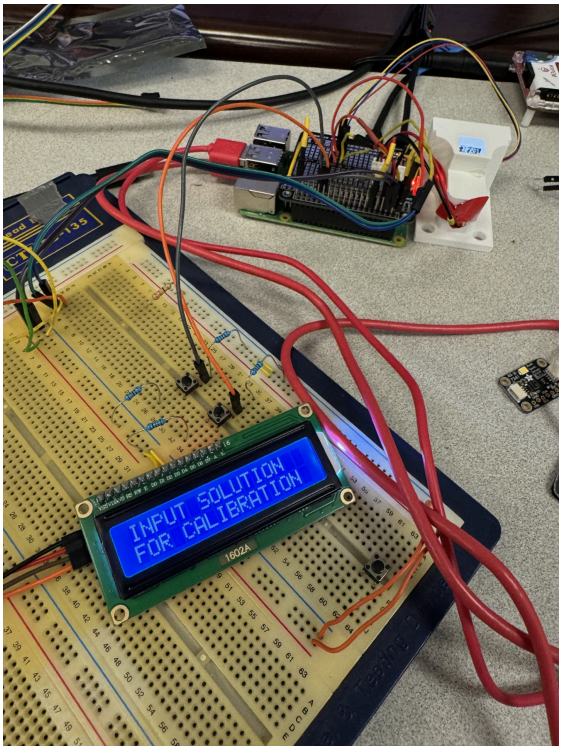
Figure 23 provides a detailed overview of the typical process involved in conducting a SPECTRA test. (a) The procedure begins with the system awaiting user input, signified by pressing a designated *start* button. (b) Following activation, the LED is calibrated by reducing the duty cycle of its PWM signal until the sensor no longer registers saturation. (c) Subsequently, SPECTRA prompts the user to input the calibration solution of distilled water. (d) The program remains paused until the user presses the *continue* button, ensuring the test proceeds only when the solution is in place. (e) Upon confirmation, the AS7341 sensor measures light intensity and indicates the ongoing measurement process to the user. (f) After completion, the system prompts the user to input the solution intended for absorbance measurement; in this case, a chlorophyll solution. (g) Again, the program awaits user action, pausing until the *continue* button is pressed to confirm solution placement. (h) Upon activation, SPECTRA commences taking light intensity measurements and indicates to the user that it has begun taking measurements. Finally, the system calculates the difference between the two light intensity measurements and communicates the detection outcome, indicating the (i) presence or (j) absence of malaria.



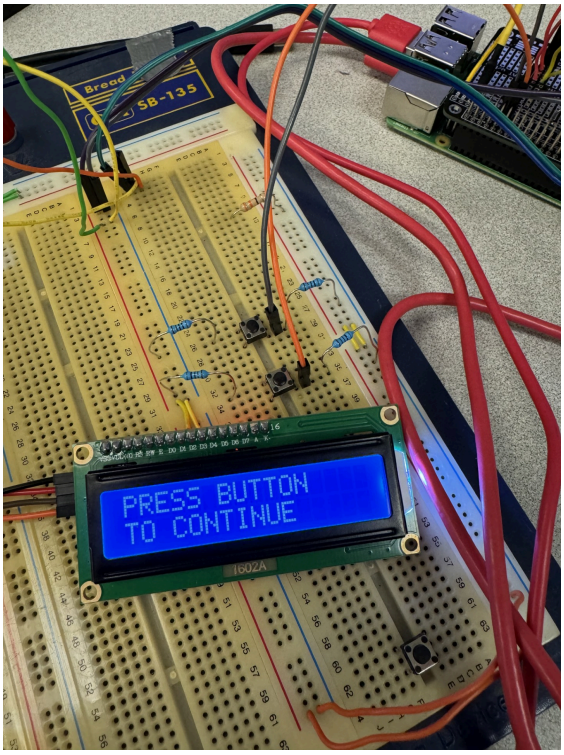
(a)



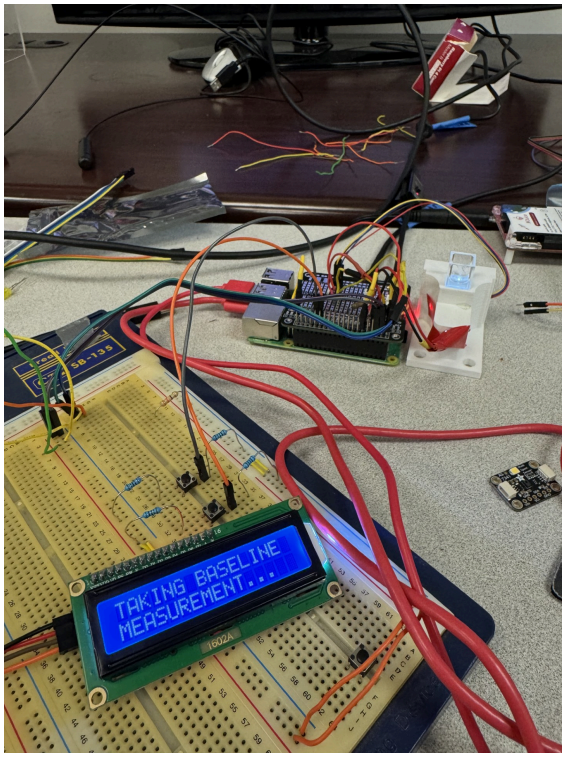
(b)


INPUT SOLUTION
FOR CALIBRATION
1602A

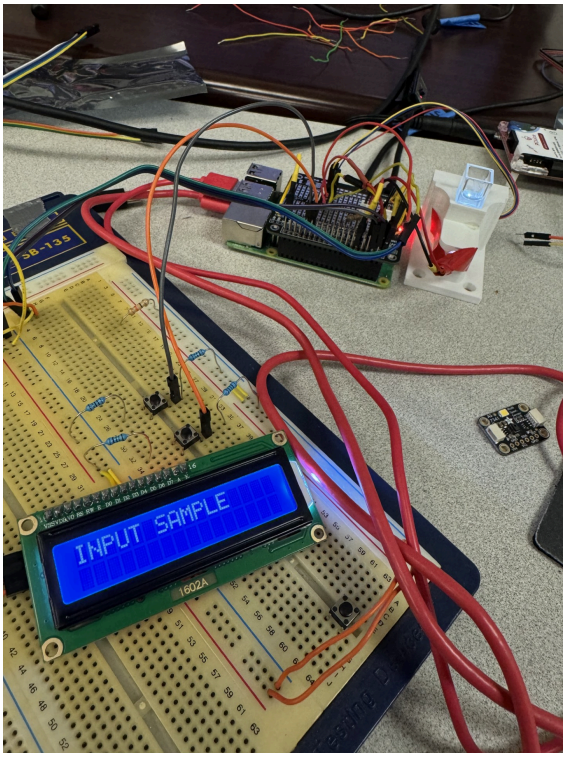
(c)


PRESS BUTTON
TO CONTINUE
1602A

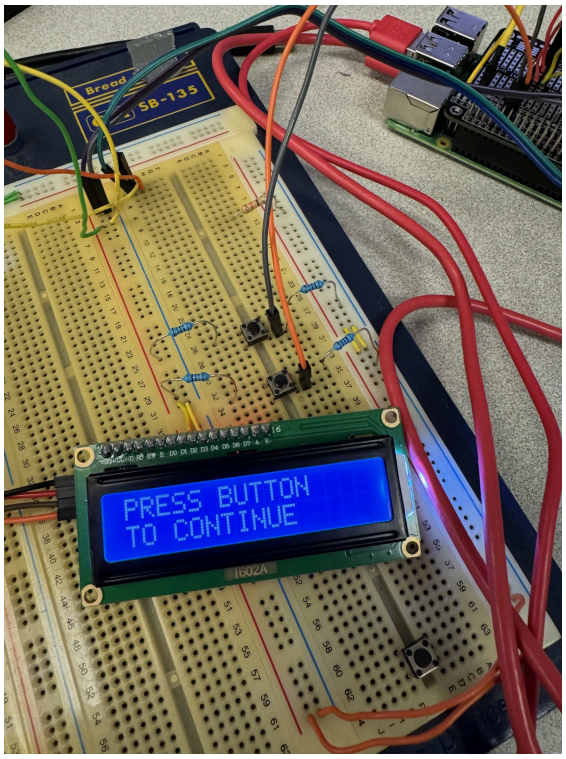
(d)


TAKING BASELINE
MEASUREMENT...
1602A

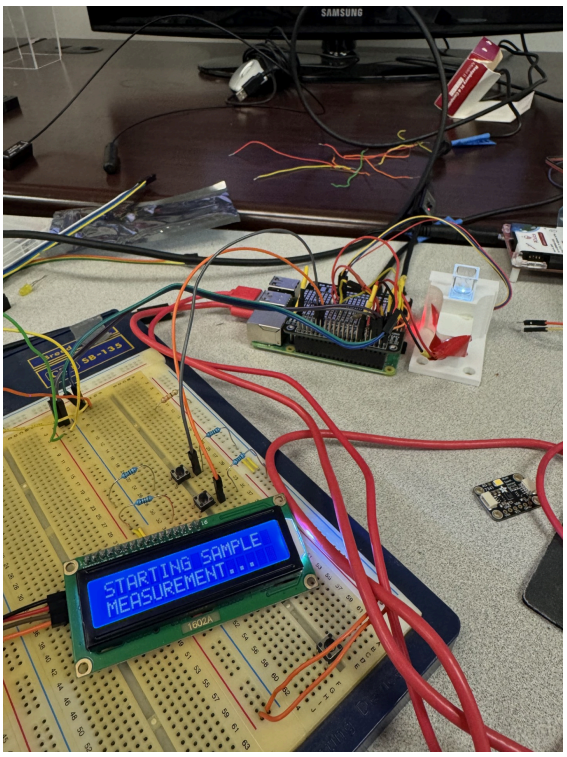
(e)


INPUT SAMPLE
1602A

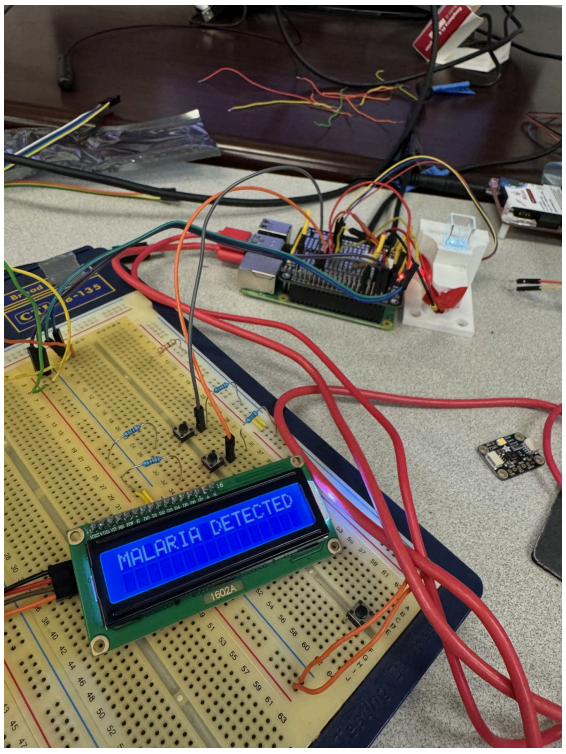
(f)



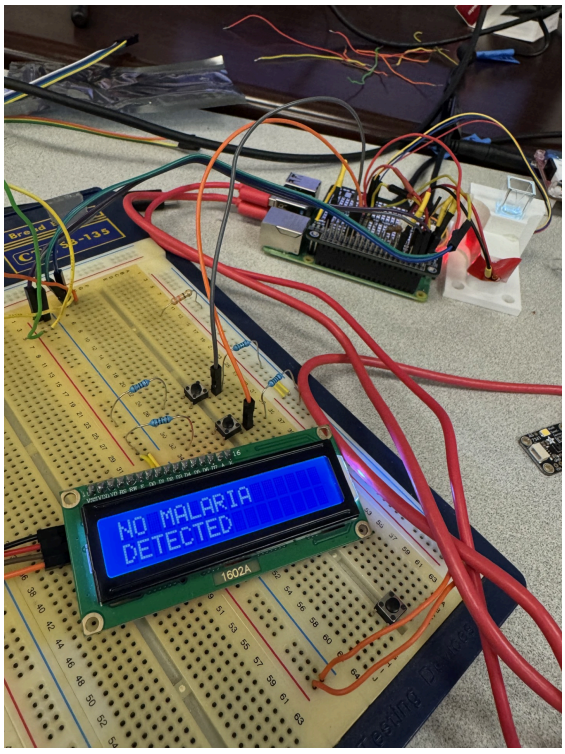
(g)



(h)



(i)



(j)

Figure 23: Sequence of a SPECTRA test procedure

5.3 Demonstration

SPECTRA's functionality and effectiveness have been demonstrated through the experiments and results described in the *Tests Used to Benchmark Performance* and *Data Analytics* sections of this report, respectively. Initial tests verified the AS7341 sensor's capability to accurately detect different wavelengths of light, while subsequent experiments addressed and mitigated saturation issues observed in the sensor. Further assessments confirmed SPECTRA's accurate detection and measurement of chlorophyll samples, and its ability to differentiate between chlorophyll solutions and other substances. Lastly, the project evaluated SPECTRA's classification performance, illustrating its true positive and true negative rates.

Overall, the experiments conducted throughout the project demonstrated SPECTRA's functionality, reliability, and alignment with both engineering and customer requirements, affirming its potential for malaria detection.

Additionally, a video showing the system and its features in operation is included in the following link and the QR code in Figure 24.

https://youtu.be/pB0t17_WeWE

Figure 24: QR code for SPECTRA video demonstration

5.4 Meeting Customer Requirements

The customer requirements are listed here again.

1. The system shall detect malaria in its Trophozoite stage.
2. The system shall be portable.
3. The system shall have a low cost.
4. The system shall be user-friendly.

Customer Requirement 1 was satisfied because SPECTRA was able to successfully detect chlorophyll at a concentration of 0.35 g/L. When malaria is in its Trophozoite stage, hemozoin,

the pigment that is being substituted for chlorophyll in this project, is present in the blood at a concentration of about 0.35 g/L [16]. During this stage of the parasite's life, the infection is still asymptomatic and undetectable by many malaria diagnostic tools [14]. Therefore, it was critical to be able to detect chlorophyll at low concentrations.

Secondly, in terms of portability, SPECTRA has been designed to meet stringent size and weight requirements, with dimensions not exceeding 1 ft by 1 ft by 1 ft and a weight of no more than 5 lb. Achieving this compact size was made possible through the use of a Raspberry Pi and a soldered PCB protoboard that sits atop the Pi, effectively reducing the device's footprint. Moreover, the total cost of the system, amounting to $165.91, falls comfortably within the $300 budget set for the project, ensuring cost-effectiveness.

Lastly, SPECTRA features a user-friendly interface comprising two buttons and an LCD screen, simplifying the testing process. Its intuitive algorithm guides users through the procedure, requiring only the press of a start test button and following prompts displayed on the LCD screen. This user-centric design enhances the overall usability and accessibility of SPECTRA, aligning it closely with customer requirements.

5.5 Data Analytics

The data analysis of SPECTRA's performance throughout the testing process reveals promising results across various experiments.

AS7341 Sensor Test:

Initially, tests on the AS7341 sensor demonstrated its ability to accurately detect different wavelengths of light, with clear distinctions observed between LEDs of varying wavelengths. Figures 25-27 show the results from the *AS7341 Sensor Test* described in the *Tests Used to Benchmark Performance*.

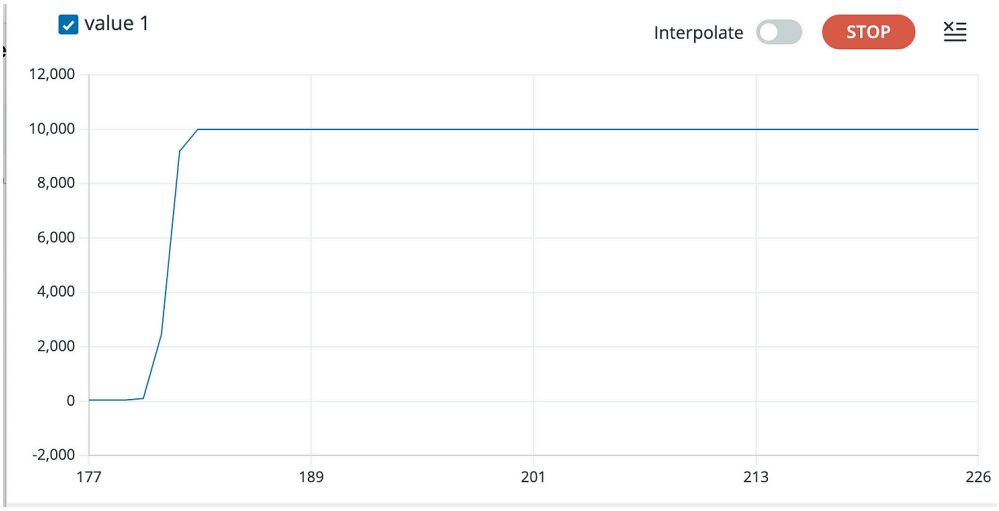


Figure 25: AS7341 response to 630 nm LED

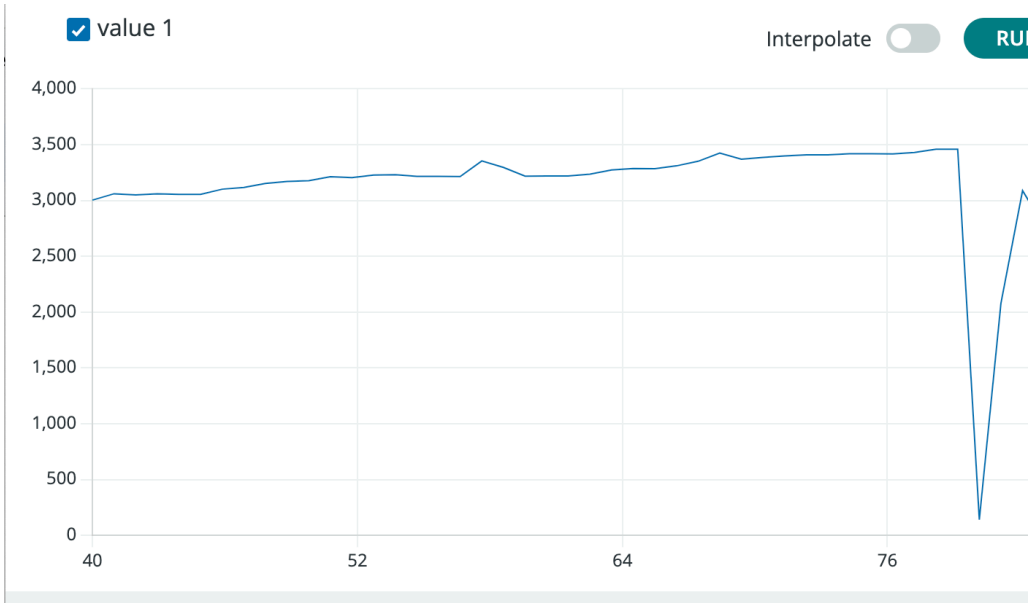


Figure 26: AS7341 response to 670 nm LED

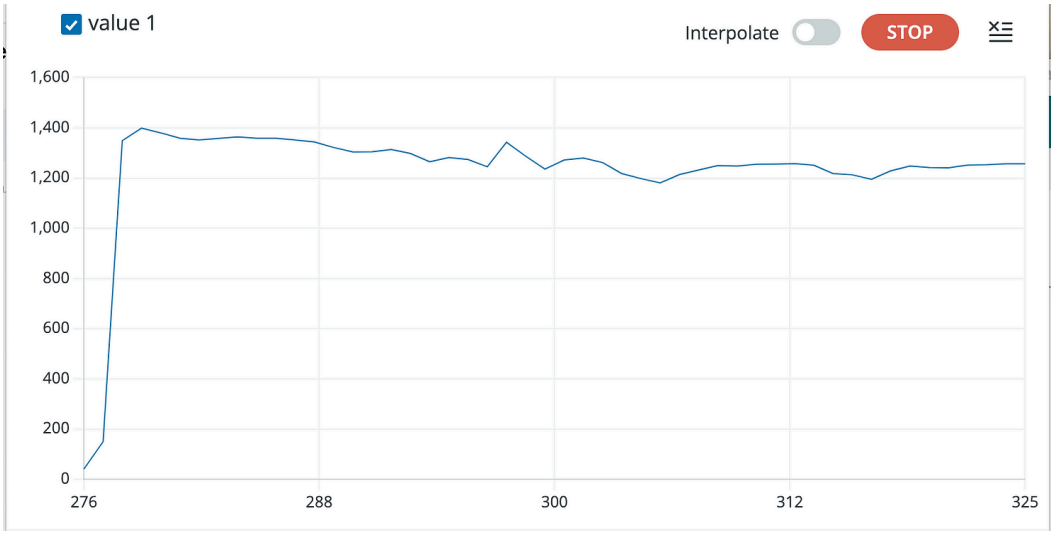


Figure 27: AS7341 response to 520 nm LED

The results from this experiment confirm the hypothesis that the AS7341 sensor's red channel would detect a higher intensity of light from the 630 nm LED compared to the 520 nm and 670 nm LEDs. As illustrated in Figure 25, the sensor recorded a light intensity of approximately 10,000 units when measuring the 630 nm LED. Conversely, Figures 26 and 27 depict lower light intensities of about 3,000 and 1,400 units, respectively, when measuring the 670 nm and 520 nm LEDs. This demonstrates the sensor's capability to accurately distinguish between different

wavelengths of light. These results show that the AS7341 is capable of differentiating between absorption at different wavelengths.

AS7341 Saturation Test with Potentiometer:

Initial observations revealed saturation in at least one channel of the AS7341 sensor, prompting exploration into alternative methods to mitigate saturation and ensure reliable measurements. Table 19, shown below, displays the results from the AS7341 Saturation Test with Potentiometer as described in the *Tests Used to Benchmark Performance* section of this report.

Table 19: Light intensity measured by AS7341 with and without a chlorophyll sample as resistance was varied

		415	445	480	515	555	590	630	680
Trial 1	no sample	10000	10000	10000	10000	10000	10000	10000	10000
	sample	2454	10000	10000	10000	10000	10000	10000	10000
Trial 2	no sample	9830	10000	10000	10000	10000	10000	10000	10000
	sample	1007	5311	5062	10000	10000	10000	7302	5021
Trial 3	no sample	7331	10000	10000	10000	10000	10000	10000	10000
	sample	867	4761	4450	10000	10000	9493	6343	4332
Trial 4	no sample	5306	10000	10000	10000	10000	10000	10000	9523
	sample	1005	5686	5235	10000	10000	10000	7634	5128
Trial 5	no sample	1237	10000	4896	9439	10000	10000	9152	3790
	sample	318	1914	1853	4511	6363	4629	3030	2156
Trial 6	no sample	663	6469	3413	6054	9060	7443	5431	2685
	sample	217	1406	1427	2849	4923	3311	1883	1719
Trial 7	no sample	542	768	2668	4861	7172	5982	4545	2106
	sample	142	908	926	2054	3204	2133	1232	1135

As seen in Table 19, at least one channel of the AS7341 sensor was saturating, reaching its maximum value of 10,000, up until Trial 6 when the potentiometer was set to 1200 Ω. Therefore, the sensor was at the point just before saturation when the LED was placed in series with a 1200 Ω resistor. However, potentiometers can be unstable and difficult to calibrate, so a different method to prevent the sensor from saturating was tested.

AS7341 Saturation Test with PWM:

Following the test with the potentiometer, a test was derived to determine whether pulse width modulation could achieve a more optimal brightness calibration for the light source. The results from this test are shown in Table 20.

Table 20: Light intensity measured by AS7341 with and without a chlorophyll sample as duty cycle was varied

	100%		80%		60%		40%		20%		0%	
Wavelength (nm)	No Sample	Sample	No Sample	Sample	No Sample	Sample	No Sample	Sample	No Sample	Sample	No Sample	Sample
415	20546	3324	12944	4839	8804	2881	7364	2450	4038	756	69	15
445	65535	18467	64586	26424	45280	15892	36853	13697	19979	4313	202	18
480	42944	13778	27294	19493	18480	11678	15642	9958	8728	3051	258	40
515	65535	35489	63028	49999	41416	29914	36065	25575	20283	7666	554	136
555	65535	46800	65535	61716	54936	35829	44395	31963	25843	9518	1016	277
590	65535	34191	65535	45009	45281	26148	36964	23369	21380	6940	917	170
630	65535	24220	50165	31794	34775	18501	28431	16483	16499	4917	957	148
680	29548	13209	19554	17258	13730	10185	11102	8987	6451	2752	389	102

Through an iterative process, it was discovered that an approximately 80% duty cycle yielded optimal calibration results for SPECTRA, eliminating saturation for all the channels on the breakout board. Using PWM to calibrate SPECTRA offers greater convenience compared to using a potentiometer due to its simpler setup, precise control over the duty cycle, and the elimination of the need for manual adjustments, making it more suitable for field deployment where access to tools like multimeters may be limited.

Low Concentration Tests:

Once PWM was shown to reduce oversaturation, testing was started to determine if SPECTRA met the threshold to detect malaria at low concentrations. Figures 28 and 29 show the results from the tests for 2 g/L solutions of aqueous chlorophyll.

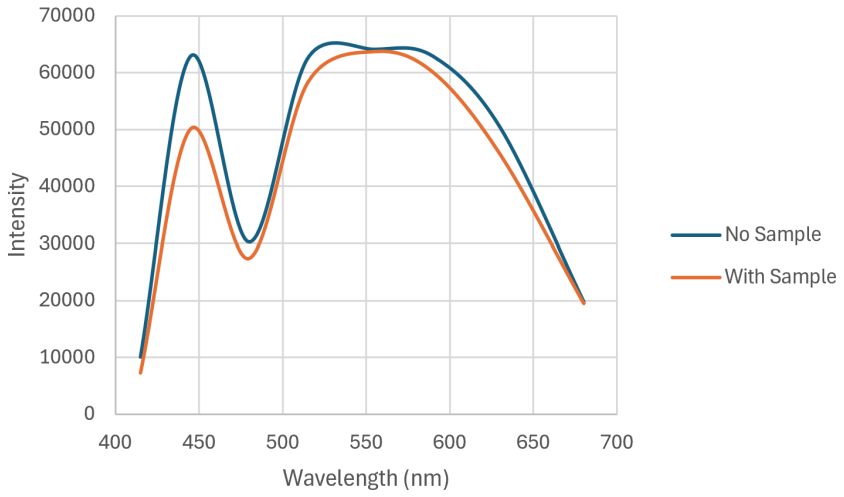


Figure 28: Light intensity measured by AS7341 when a 2 g/L solution of chlorophyll was tested

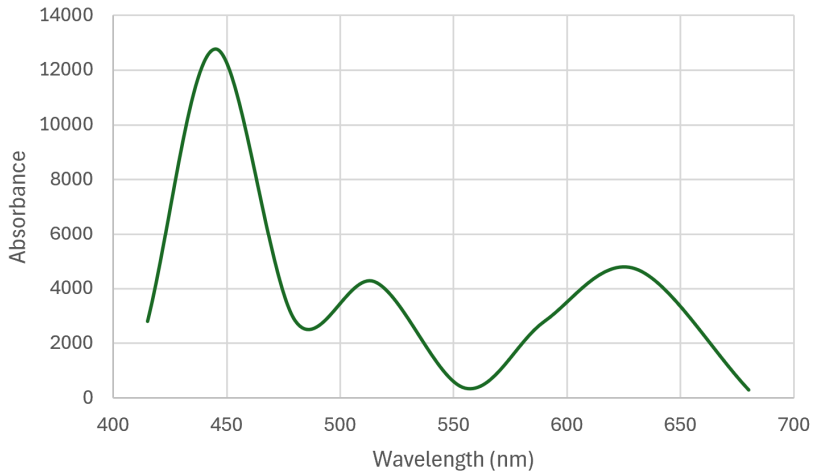


Figure 29: Calculated absorbance of a 2 g/L solution of chlorophyll

Figure 28 shows the results from the test using a solution with a 2 g/L concentration of chlorophyll. The blue line shows the sensor readings when a cuvette with distilled water was inserted into the device, and the orange line shows the sensor readings when the chlorophyll solution was inserted. Figure 29 shows the difference between the blue and orange lines, giving a graphical view of the total absorbance detected by SPECTRA. Figures 30 and 31 show the results for 1g/L chlorophyll solution.

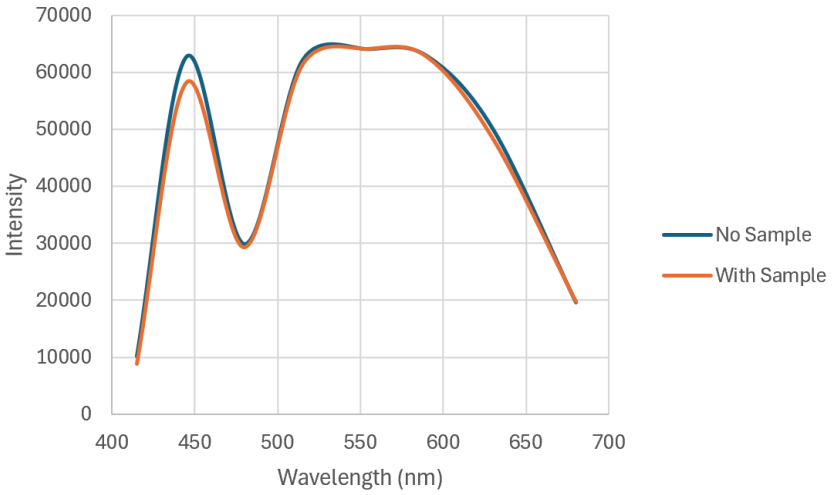


Figure 30: Light intensity measured by AS7341 when a 1 g/L solution of chlorophyll was tested

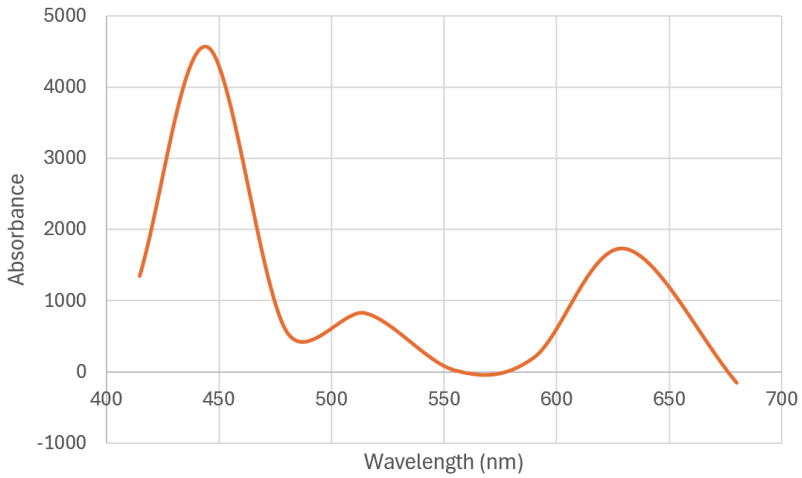


Figure 31: Calculated absorbance of a 1 g/L solution of chlorophyll

Figure 30 shows the results from the test using a solution with a 1 g/L concentration of chlorophyll. Again, the blue line shows the sensor readings when a cuvette with distilled water was inserted into the device, and the orange line shows the sensor readings when the chlorophyll solution was inserted. Figure 31 shows the difference between the blue and orange lines, giving a graphical view of the total absorbance detected by SPECTRA. Lastly, Figures 32 and 33 show the results from testing solutions of 0.35 g/L, the threshold for asymptomatic malaria.

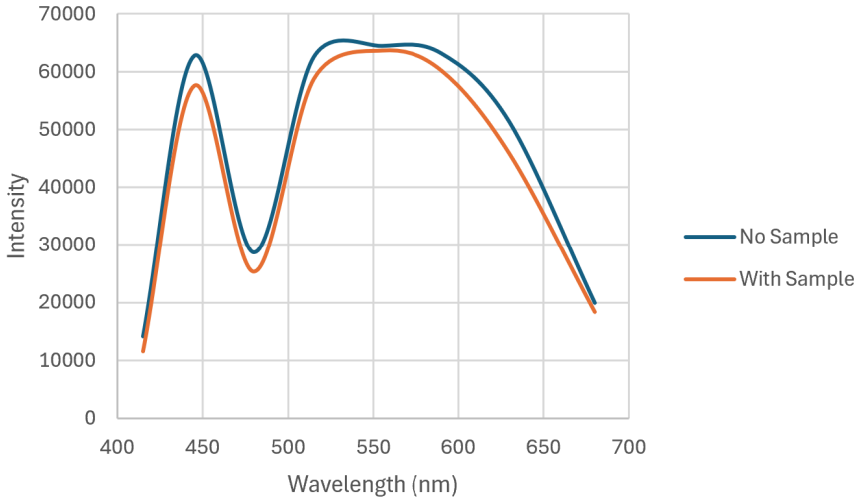


Figure 32: Light intensity measured by AS7341 when a 0.35 g/L solution of chlorophyll was tested

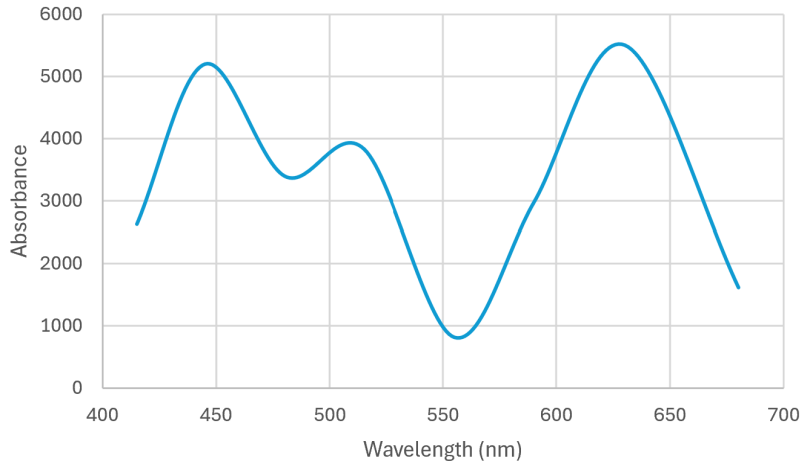


Figure 33: Calculated absorbance of a 0.35 g/L solution of chlorophyll

In, Figure 32 the blue line shows the sensor readings when a cuvette with distilled water was inserted into the device, and the orange line shows the sensor readings when the chlorophyll solution was inserted. Again, Figure 33 shows the difference between the blue and orange lines, giving a graphical view of the total absorbance detected by SPECTRA.

It can be seen that the total absorbance detected for the three different solutions is relatively consistent with the absorption spectrum of chlorophyll measured with the spectrometer provided by the chemistry department, shown in Figure 17. This consistency validates SPECTRA's accuracy in detecting and measuring chlorophyll concentrations.

Chlorophyll vs. Dyed Solutions Test:

Once tests were done with chlorophyll solutions, a test was derived to determine whether SPECTRA could differentiate chlorophyll solutions and other dyed solutions. The spectrometer from the chemistry department was used to measure the absorption spectrum of three different dyed solutions. Figures 34-36 show the absorption spectrum for each of the dyed solutions: Blue Powerade, Orange Fanta, and Red Powerade, respectively.

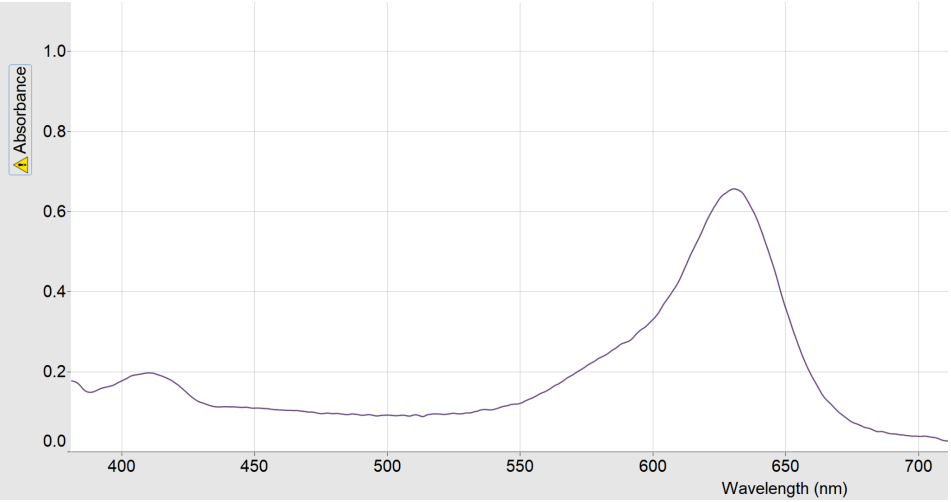


Figure 34: Absorption spectrum of Blue Powerade

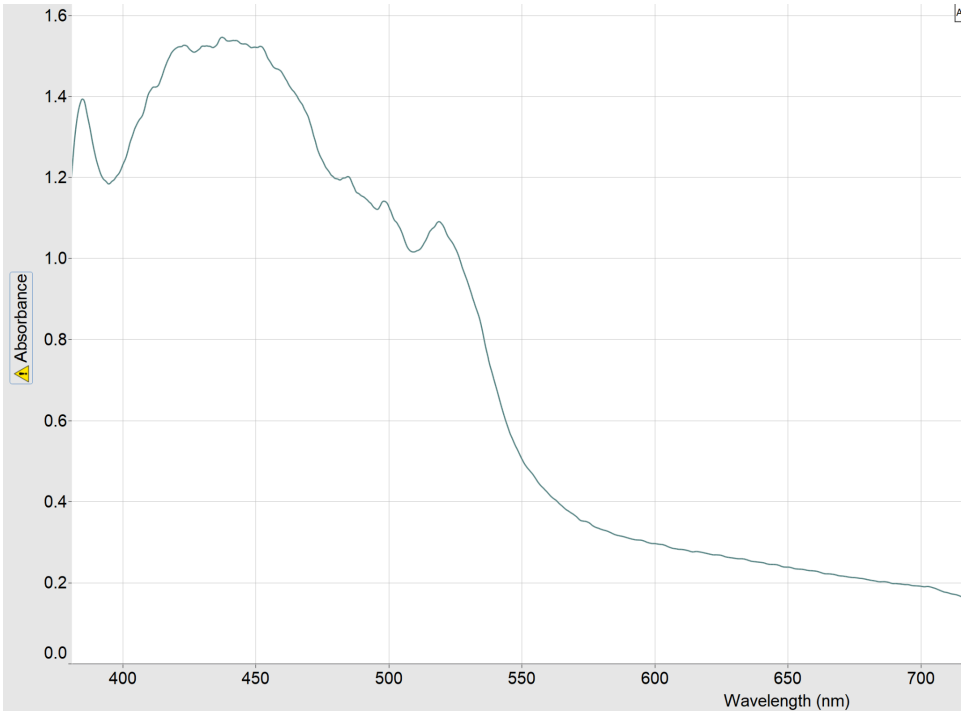


Figure 35: Absorption spectrum of Orange Fanta

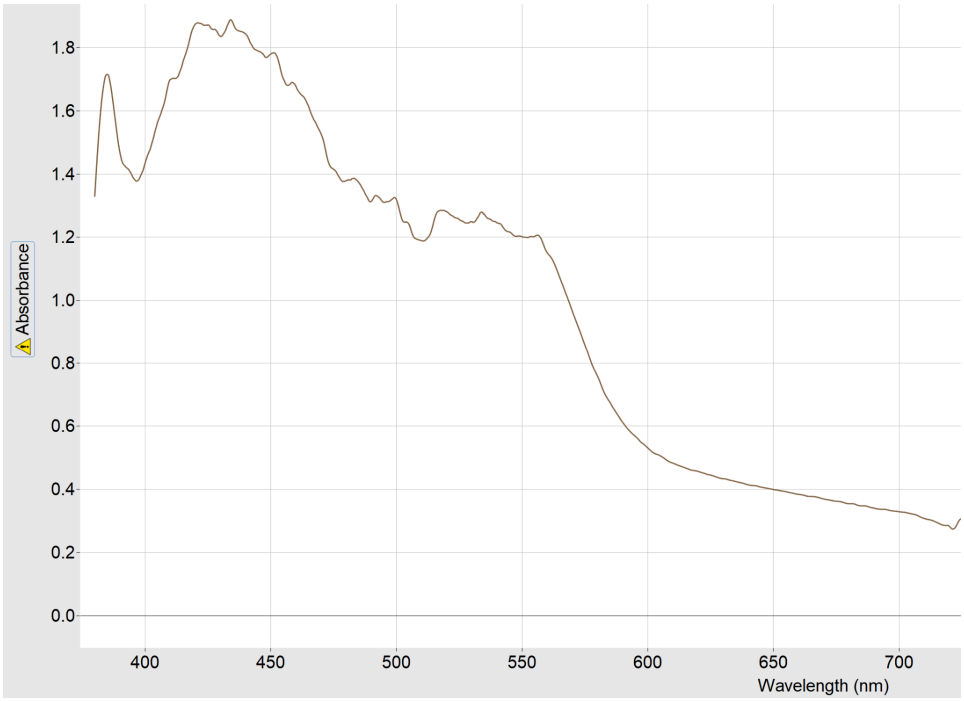


Figure 36: Absorption spectrum of Red Powerade

After the chemistry department's spectrometer was used to measure the absorption spectrum of the solutions, SPECTRA was used to measure each of the solutions to see if it could accurately distinguish between them all. A sample of distilled water was used to generate a baseline measurement for light intensity values before each of the testing solutions was placed into SPECTRA. Absorbance values measured by SPECTRA for each solution are depicted in Figure 37.

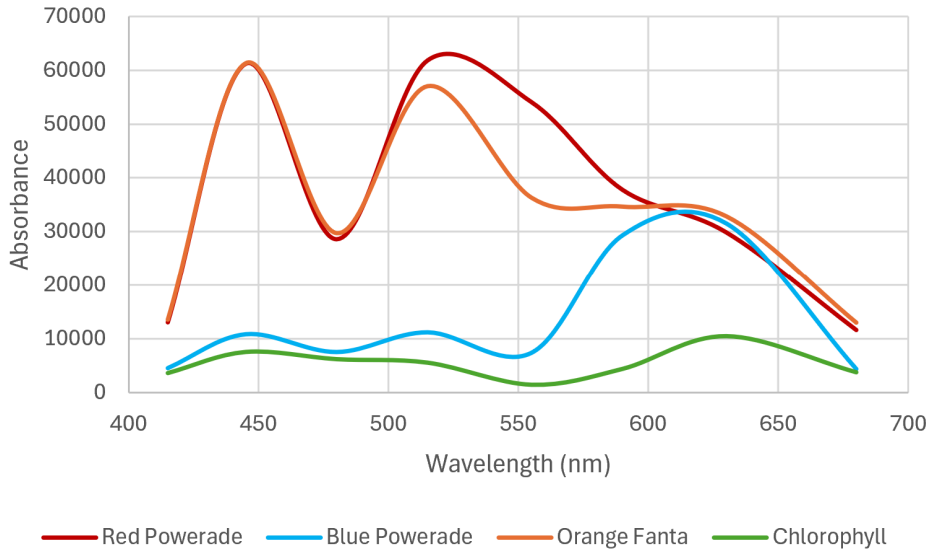


Figure 37: Absorption spectrum of Red Powerade, Blue Powerade, Orange Fanta, and Chlorophyll measured by SPECTRA

As shown in Figure 37, SPECTRA accurately measured the absorption spectrum for each solution. This successful differentiation between chlorophyll and other substances emphasizes the device's capability for precise spectral analysis, affirming its potential for malaria detection.

Accuracy Rate:

Once tests were done with low concentrations, the true and false positive and negative rates were calculated. The results of these tests are shown in Table 21.

Table 21: Confusion matrix for SPECTRA's classification performance

	Actual Positive (Chlorophyll)	Actual Negative (Water)
Predicted Positive	True Positive (16) 80%	False Positive (1) 5%
Predicted Negative	False Negative (4) 20%	True Negative (19) 95%

The results show a true positive rate of 80%, indicating that SPECTRA accurately detected chlorophyll in the samples. Additionally, the false positive rate was measured at 5%, suggesting a low occurrence of incorrect identifications. These findings display the device's effectiveness in distinguishing between target solutions and other solutions.

6 Ethics Considerations

The following criteria were examined when analyzing the ethical considerations for SPECTRA. First, the collection of blood samples for the SPECTRA tests will prioritize the well-being of participants. The process will be conducted in a respectful and considerate manner, ensuring minimal discomfort for participants. Additionally, because malaria is a more significant issue in less affluent countries, special attention will be given to ensure equitable access to SPECTRA. The project will adhere to the predefined cost limit to ensure its affordability, and measures will be taken to minimize the economic barriers to access. Lastly, maintaining the highest standards of accuracy and reliability for SPECTRA is paramount. Stringent testing protocols will be followed to minimize the risk of misdiagnoses, recognizing the severe consequences that may arise from inaccurate results.

7 Contribution to ABET Program, LMU Mission and Values, Diversity, Social Community, Multidisciplinary Nature, and IEEE Values

7.1 Contribution to ABET Program

The Accreditation Board for Engineering and Technology (ABET) has outlined several student outcomes [17]. This project contributes to all seven of the ABET student outcomes.

The first outcome states that students should have “an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.” This project involves the identification and formulation of a complex engineering problem related to malaria diagnosis. The engineering problem lies in the limitations of current testing methods for asymptomatic cases. The development of the solution, SPECTRA, involves the integration of scientific knowledge about malaria parasites, absorption spectrometry, and mathematical algorithms for data analysis.

The second ABET outcome states, “an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.” The SPECTRA project centers around engineering design, aiming to produce a diagnostic solution tailored to meet the specific needs of detecting malaria in its early stages. The design process involves considerations of usability, portability, cost-effectiveness, and sensitivity. Health concerns are addressed by focusing on the early detection of malaria, contributing to timely and effective intervention of a global health issue. Lastly, this device is intended for use in resource-limited areas, and its affordability and portability make it suitable for diverse cultural and economic contexts.

Outcome (3) is the “ability to communicate effectively with a range of audiences.” This outcome was demonstrated through the presentations that Christopher and Adrian conducted to students, faculty, and industry professionals. Additionally, this report itself demonstrates an ability to communicate effectively with many audiences.

The fourth outcome is “an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.” As previously stated, the ethical responsibilities acknowledged by this project include obtaining informed consent for blood sample testing, ensuring diagnosis accuracy, and addressing the potential societal impact of the device on malaria diagnosis. Consideration of economic factors, accessibility, and the potential societal benefits of SPECTRA reflects a commitment to ethical

decision-making. The project aims to balance the economic feasibility of the device with its potential positive impact on society by making sure to keep the device affordable.

Outcome (5) is “an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.” Adrian and Christopher have worked collaboratively, establishing goals, planning tasks, and meeting objectives. They have created an inclusive environment, allowing them to work effectively and efficiently to complete their assigned tasks and deliverables.

Outcome (6) is the “ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.” The SPECTRA project involves the development and conduct of experimentation to validate the device’s functionality. Preliminary tests were conducted in conjunction with the chemistry department to get the data for the absorption spectrum of hemozoin. In addition, experiments to test the wavelength spectrum of the deep red LED and the accuracy of the light sensor were conducted. More experiments will be conducted, and analysis skills will be employed to interpret the results, in order to test the accuracy and reliability of SPECTRA.

The seventh outcome is the “ability to acquire and apply new knowledge as needed, using appropriate learning strategies.” Throughout the duration of this project, Adrian and Christopher have conducted much research in the field of spectroscopy, existing malaria diagnosis products, and available electronic components in the market. They implemented their acquired knowledge to design, build, and test SPECTRA.

7.2 Contribution to LMU Mission and Values

This project aligns with Loyola Marymount University’s mission by actively contributing to the university’s core principles of the encouragement of learning, the education of the whole person, and the service of faith and the promotion of justice [18]. The project embodies the spirit of encouraging learning by engaging in research and development; Adrian and Christopher actively seek to expand their knowledge in fields such as spectroscopy, optics, and electronics. Additionally, the SPECTRA project contributes to the education of the whole person by fostering a holistic approach to problem-solving. Team members are not only learning about electrical engineering concepts, but also topics in biology, technical skills, critical thinking, communication, and collaboration abilities. Moreover, team members must think beyond technical solutions, considering the societal and ethical implications of SPECTRA. Lastly, this project aligns with the service of faith and the promotion of justice by addressing a health issue that disproportionately affects vulnerable populations, particularly in resource-limited areas. The development of an affordable and portable malaria diagnostic tool reflects a commitment to service and justice.

7.3 Diversity

This project contributes to diversity in several meaningful ways. First, malaria is a global health challenge that transcends borders and affects people from various backgrounds. SPECTRA's goal of providing an affordable and efficient diagnostic solution contributes to global health equity, addressing the needs of diverse populations around the world. Additionally, health disparities often affect minority populations disproportionately. By providing an affordable and accurate diagnostic tool for malaria, SPECTRA contributes to mitigating health disparities linked to this infectious disease. Lastly, the emphasis on a user-friendly interface in SPECTRA recognizes the diversity in the skill sets and technical expertise of healthcare workers in different regions. The device's simplicity and ease of use allow individuals with varying levels of training to administer malaria tests, ensuring that the benefits of accurate diagnostics reach diverse healthcare settings.

7.4 Social Community

The SPECTRA project contributes significantly to the social community by addressing critical healthcare needs and promoting overall well-being. SPECTRA aims to bring accurate and affordable malaria diagnosis to communities, particularly in regions with limited access to healthcare resources. By providing a portable and cost-effective diagnostic tool, the project contributes to closing the healthcare accessibility gap, ensuring that individuals in diverse communities can receive timely and effective malaria testing.

7.5 Multidisciplinary Nature

The technical nature of this project intersects with chemistry, biology, and mechanical engineering. This project draws on knowledge from biomedical sciences to understand the biology of malaria, specifically the presence of hemozoin as a biomarker in infected blood. This expertise informs the development of the diagnostic method using spectrophotometry. Additionally, spectroscopy is a fundamental technique used in the project for analyzing the absorption spectrum of hemozoin. Knowledge of chemistry and spectroscopy is applied to interpret the spectral data and develop an effective diagnostic method. Christopher and Adrian consulted with experts in both biology and chemistry to develop and facilitate solutions for this project.

7.6 Compliance with IEEE Code of Ethics

This capstone project demonstrates strong compliance with the IEEE Code of Ethics by prioritizing integrity, responsible behavior, and ethical conduct in all aspects of its development [19]. The first IEEE Code of Ethics pillar is "to uphold the highest standards of integrity, responsible behavior, and ethical conduct in professional activities." SPECTRA prioritizes the safety, health, and welfare of the public by aiming to provide an affordable and portable

diagnostic tool to address the global health issue of malaria. Additionally, the project is committed to ethical design practices, ensuring that the technology developed addresses societal needs responsibly. The second pillar is “to treat all persons fairly and with respect, to not engage in harassment or discrimination, and to avoid injuring others.” SPECTRA ensures that no harm is inflicted on individuals, ensuring the least invasive sample acquisition as possible and accurate results. The third pillar is to “strive to ensure this code is upheld by colleagues and co-workers.” Christopher and Adrian both strive to support and encourage each other to make sure the IEEE Code of Ethics is upheld.

8 Conclusion

Malaria poses a significant public health threat to over 3 billion people annually. Studies among these infected individuals have shown that as many as 75% of these cases can be asymptomatic [20]. These cases are often harder to detect due to a lower concentration of a biomarker in malaria called hemozoin. Unfortunately, tests that are capable of detecting at low concentrations are often expensive. Therefore, for healthcare solutions to be deployed to the affected population, testing procedures need to become more effective both in cost and analysis. To help expand testing capabilities at a reduced cost, a spectrophotometric malaria detection device was developed.

The designed system is effectively able to detect chlorophyll, a stand-in for the hemozoin biomarker, at concentrations of 0.35 g/L. This concentration was identified as the detection threshold for the device as hemozoin levels at or below this concentration typically correspond to asymptomatic cases of malaria [16]. Testing revealed that the true positive rate of SPECTRA for the detection of chlorophyll at this concentration was 80%, indicating that the device accurately detected chlorophyll in the samples at a rate consistent with most RDTs on the market. Additionally, the false positive rate was measured to be 5%, suggesting a low occurrence of incorrect identifications. For $165, this device is significantly more affordable than most handheld spectrophotometers, enhancing accessibility, especially in resource-limited settings. Featuring a user-friendly interface and lightweight case, it ensures ease of use and portability, making it invaluable in diverse healthcare settings.

This device has the potential to impact the healthcare of billions worldwide. It would not only be a viable alternative to traditional testing methods but in many cases an improvement.

9 Suggestions

SPECTRA on its own could be a valuable tool in the world of malaria diagnostics. However, as a prototype, it has several areas which could and should be improved. The first element that should be improved is the sample size. Currently, the prototype requires roughly 1-2ml of aqueous

chlorophyll solution for testing. If the sample size was this large, it would require the patient to input a significant amount of blood. Additionally, for those who are anemic or hemophilic, this could be a hazardous amount. A method that would lower the sample size is using fluorescence spectroscopy to detect malaria. This would significantly improve the SNR, potentially removing the need for sample collection.

SPECTRA could also be improved upon by replacing the Raspberry Pi with a microprocessor. Currently, the bulk of the SPECTRA prototype consists of the Raspberry Pi. However, having an entire computer in SPECTRA is not necessary. A much better solution would be opting for a microprocessor on a PCB. This would reduce the size and cost of the device.

Another element of SPECTRA that could be improved is its aesthetics. A more streamlined and aesthetically pleasing design would better reflect the innovative nature of the product, akin to the sleek and futuristic design of the iPhone. The device's boxy look could be modified to be smooth and pleasing to the touch. Its color could be swapped for white thermoplastic rubber which is often used in medical devices to evoke a sense of cleanliness and professionalism.

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Appendices

1. Detailed Schedule
    a. Figure 1: Gantt chart for the week of September 25 to November 13
    b. Figure 2: Gantt chart for the week of November 20 to January 8
    c. Figure 3: Gantt chart for the week of January 15 to March 4
    d. Figure 4: Gantt chart for the week of March 11 to April 29
2. Teammate Roles and Responsibilities
3. Test Plan
    a. Light Sensor
    b. Reference Curves
    c. SPECTRA
4. Code

1a.

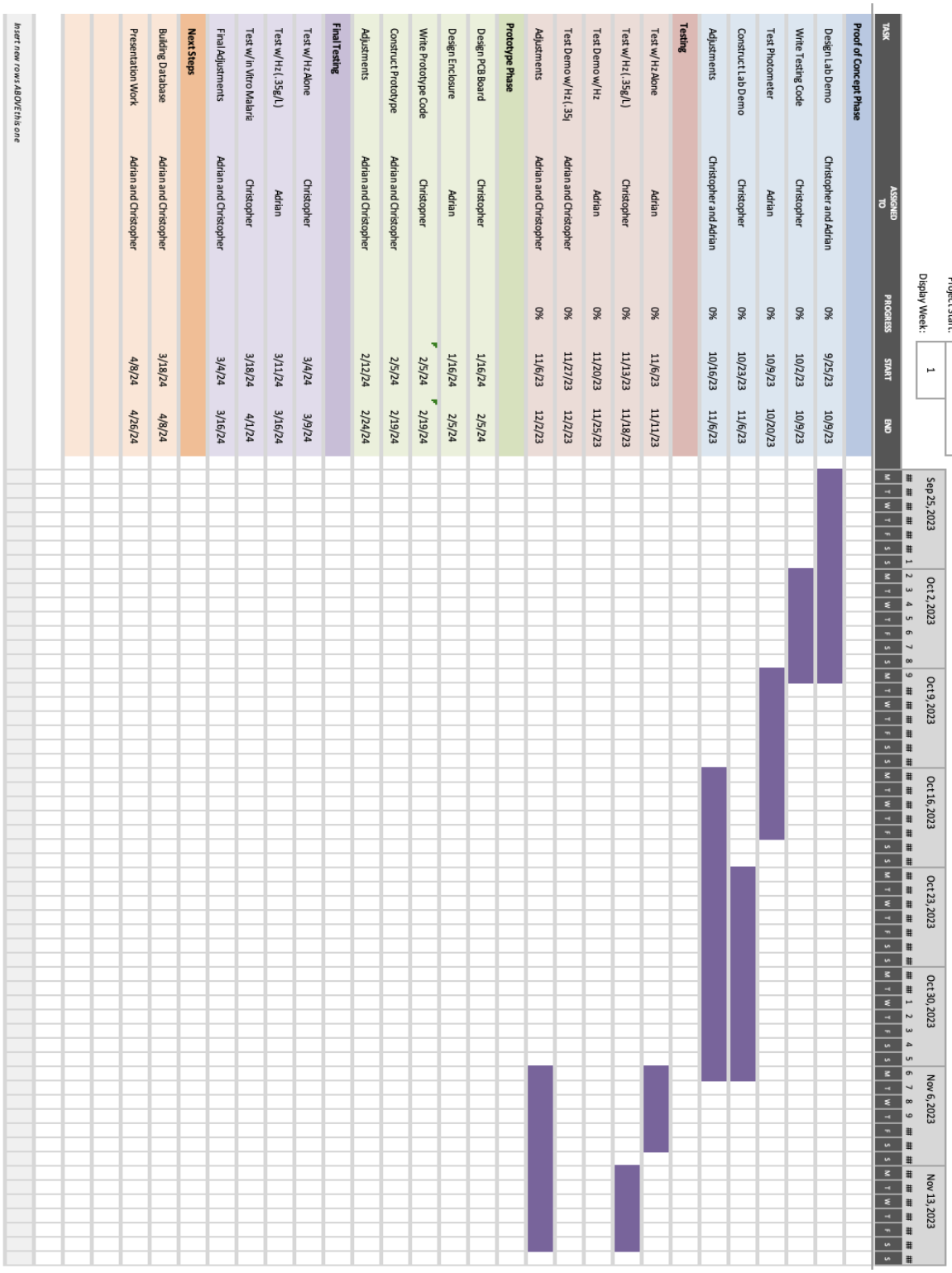

Figure 1: Gantt chart for the week of September 25 to November 13

1b.

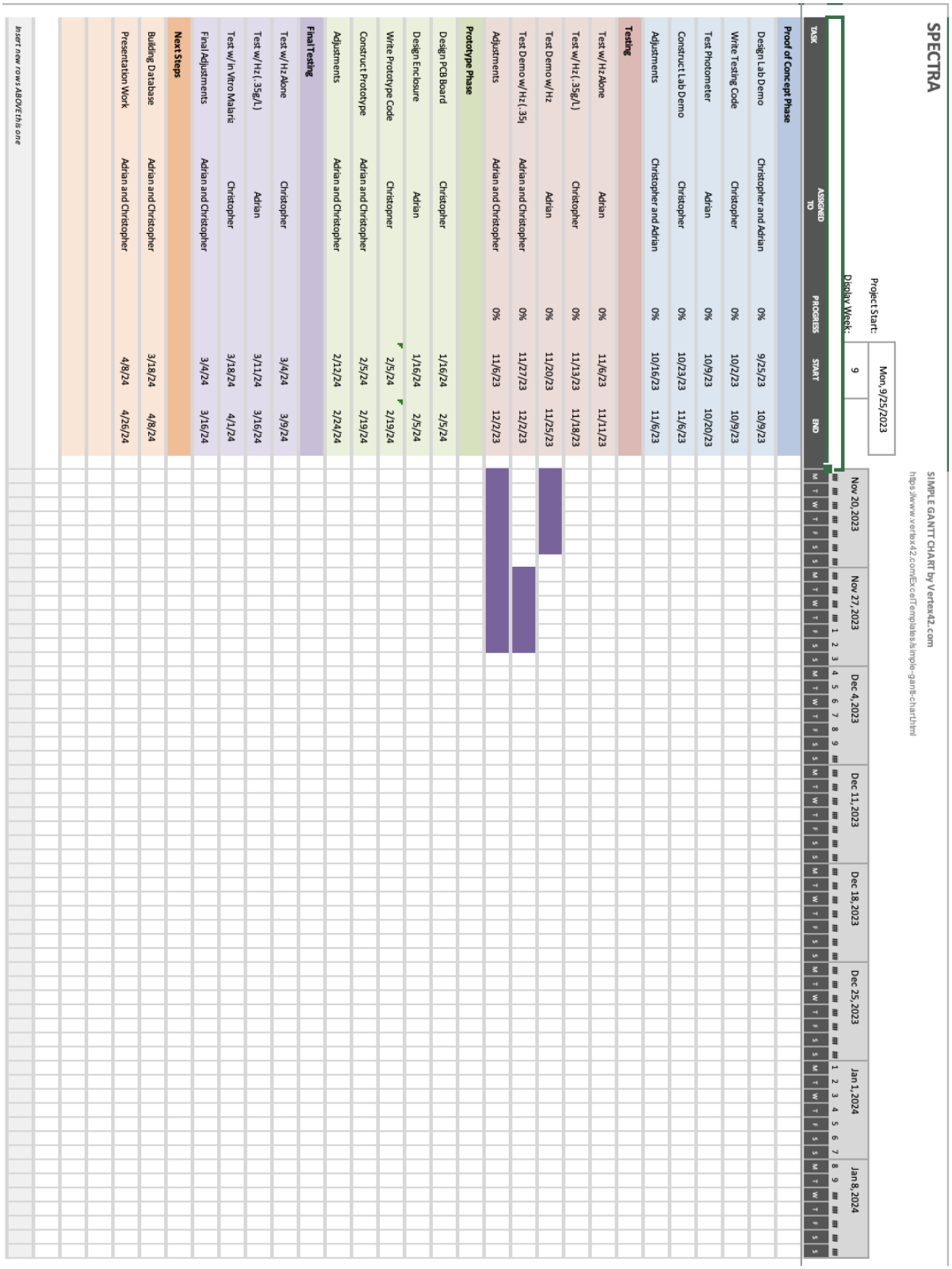

Figure 2: Gantt chart for the week of November 20 to January 8

1c.

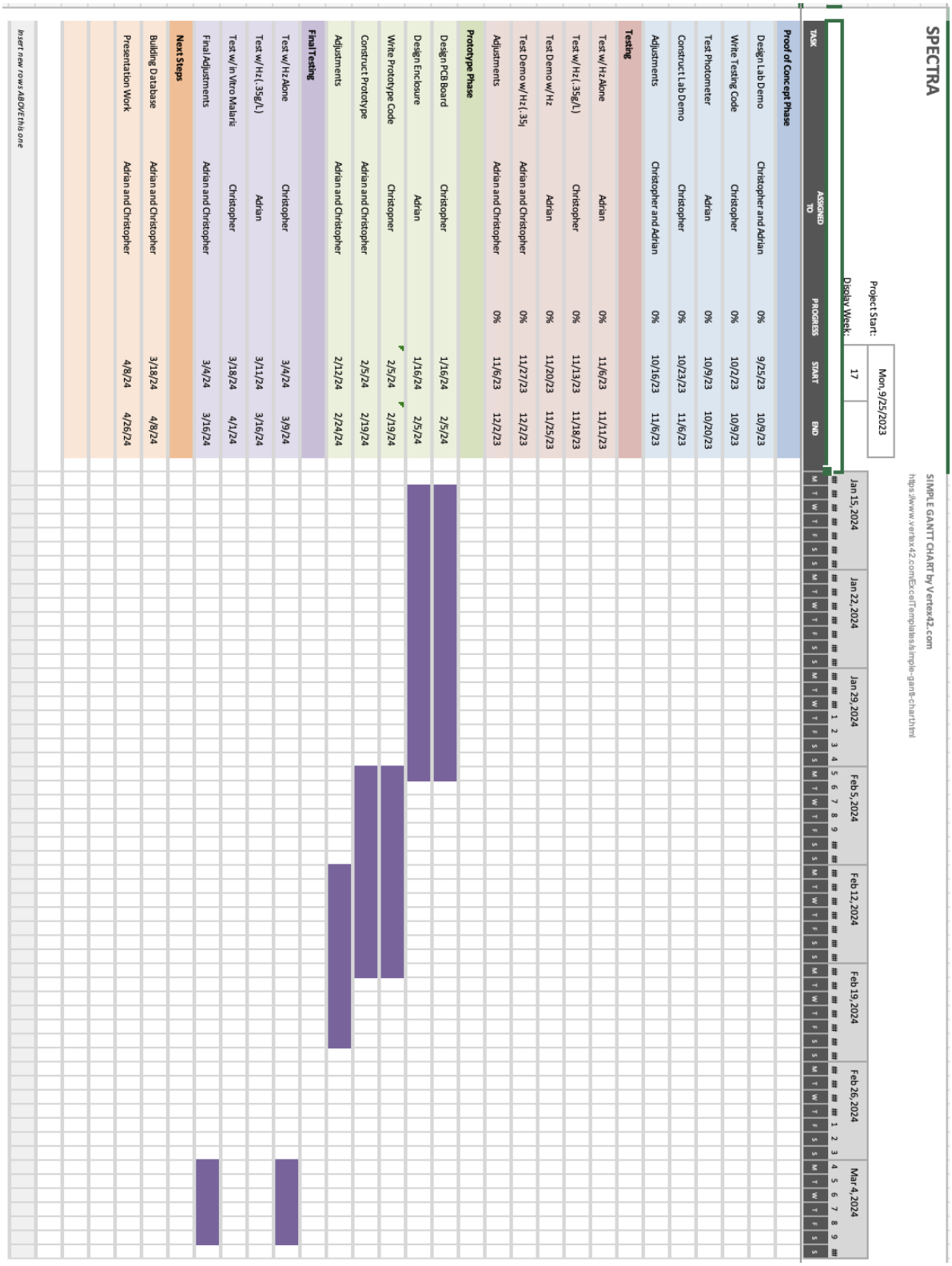

Figure 3: Gantt chart for the week of January 15 to March 4

1d.

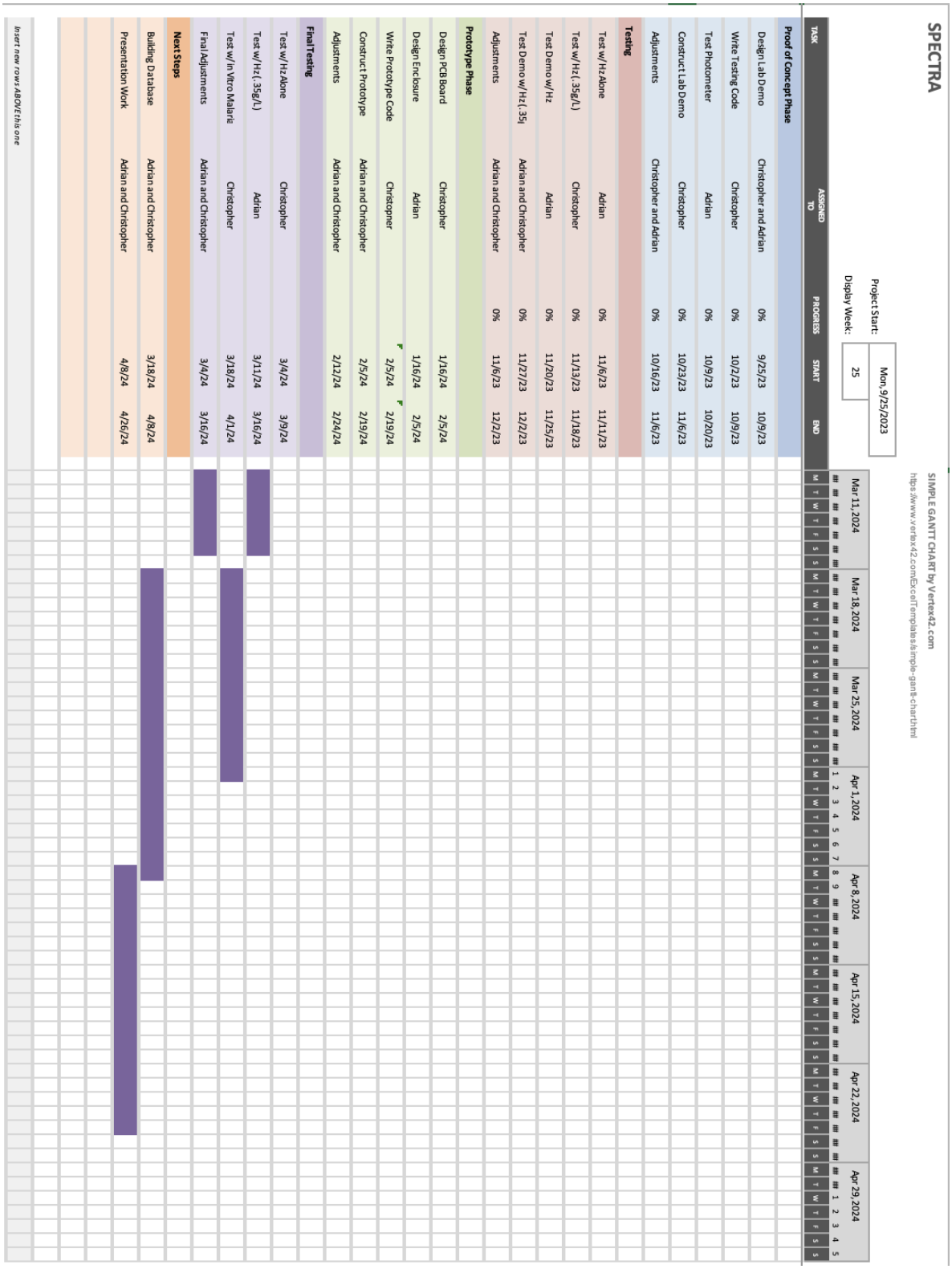

Figure 4: Gantt chart for the week of March 11 to April 29

2. Teammate Roles & Responsibilities

Throughout the development of this project, both Adrian and Christopher have worked very closely together to ensure the timely and proper development of SPECTRA. However, Christopher led the initiative of researching and handling hardware components, ensuring seamless integration into the overall system. This included integrating various sensors into the system, overseeing the construction of the SPECTRA prototype, and managing the microprocessor aspects. Adrian led much of the research and software development for SPECTRA. Some of the responsibilities include the development of the algorithms necessary for hemozoin detection, designing a user-friendly interface, and implementing the data processing algorithms to interpret the absorption spectrum data measured by the sensors.

Additionally, both students collaborated closely during the testing phases of SPECTRA. This included testing each individual component of SPECTRA, mainly the light source and the light detector, to ensure their proper functionality. Moreover, both students worked to make informed decisions about the necessary components and steps to ensure a functioning sstem, implementing actions to enhance the efficiency, safety, and functionality of SPECTRA. Lastly, both students worked closely with experts in both biology and chemistry to ensure the best possible design for SPECTRA.

3a. *Test Plan - Light Sensor*

Purpose:

The AS7341 light sensor is designed to detect subtle variations in ambient light levels. It is crucial for the sensor to exhibit both high responsivity to changes in light intensity and a stable output. These tests assess the photodiode's response to constant illumination and darkness, aiming for consistent output when exposed to a stable light source or darkness.

Objectives:

Determine the stability of the voltage across the AS7341 light sensor when an unchanging input is applied to it. The voltage is measured by the Tektronix TBS1052C Oscilloscope which has an input sensitivity that ranges from 1mV/div to 10V/div.

Procedure:

1. Set up the testing environment in a controlled space with minimal ambient light interference.
2. Ensure that the AS7341 light sensor is powered on and properly connected to the oscilloscope.
3. Record the initial voltage output of the AS7341 light sensor in complete darkness to serve as the baseline measurement.
4. Observe and document any fluctuations or stability in the output voltage.

5. Expose the light sensor to a stable and constant light source and record the output voltage on the oscilloscope over an interval of thirty seconds.
6. Observe and document any fluctuations or stability in the output voltage.

Expected Results:

The AS7341 light sensor should demonstrate a consistent and stable output voltage under both constant illumination and darkness conditions. When the sensor is exposed to a constant light source, the voltage across it should remain stable with minimal fluctuations. When the light sensor is in complete darkness, the voltage across it should remain at a baseline level with minimal fluctuations. If the oscilloscope readings align with the expected behavior, this indicates that the sensor is functioning as intended.

3b. ***Test Plan - Reference Curves***

Purpose:

The absorption curve is crucial for calibrating SPECTRA. This experiment ensures that your handheld device can precisely identify and measure hemozoin concentrations by comparing the absorption characteristics to the established reference curve. In place of hemozoin, chlorophyll will be used since it has the same absorption peak and the concentration can be more easily adjusted.

Objectives:

The objectives of this test are to generate a baseline for hemozoin's absorption curve. Two experiments will be done, first utilizing coffee grounds to mimic the particulates found in Hemozoin, and second using chlorophyll to generate the baseline curve.

Procedure:

1. Turn spectrometer on and run with no sample to calibrate
2. Weigh sample of chlorophyll
3. Stir sample into 1L of water
4. Place 5ml of the solution into cuvette
5. Run spectrometer and log the data that is output
6. Repeat steps 2-5 for the sample with concentrations of chlorophyll from 0.5g/L to 0.05g/L
7. Recalibrate spectrometer
8. Weigh sample of coffee grounds
9. Stir sample into 1L of water
10. Place 5ml of the solution into cuevett
11. Run spectrometer and log the data that is output
12. Repeat steps 2-5 for the sample with concentrations of chlorophyll from 0.5g/L to 0.05g/L

Expected Results: The absorption curve for the chlorophyll should have a peak from 650-670nm with a decrease in resolution as the concentration is decreased. The coffee grounds should see a similar curve but with a lower resolution due to the particulates.

3c. *Test Plan - SPECTRA*

Purpose:

SPECTRA is a device designed to detect malaria in a blood sample. It does so by detecting hemozoin, a pigment found in malaria, using absorption spectroscopy. The purpose of this test is to determine the proper functionality of the SPECTRA prototype.

Objectives:

The objectives of this test are to determine, firstly, if SPECTRA can detect hemozoin in high concentrations in a sample and, secondly, if SPECTRA can detect hemozoin at a concentration of 0.35 g/L in a sample.

Procedure:

1. Ensure that the SPECTRA prototype is properly calibrated, powered on, and connected to the necessary equipment.
2. Weigh a sample of hemozoin.
3. Stir the sample into 1 L of water.
4. Place 5 ml of the solution into the cuvette.
5. Run the spectrometer and log the data that is output.
6. Repeat steps 2-5 for the sample with concentrations of hemozoin from 0.5g/L to 0.05g/L.
7. Verify that the high hemozoin samples are prepared and labeled correctly.
8. Introduce the sample with a 0.5 g/L concentration of hemozoin to the SPECTRA prototype.
9. Record and analyze the absorption spectrum data obtained by SPECTRA.
10. Verify if the device accurately detects and identifies the 0.5 g/L concentration of hemozoin in the sample.
11. Repeat steps 8-10 for all the hemozoin solutions.

Expected Results:

SPECTRA is anticipated to accurately and consistently detect and identify both high and low concentrations of hemozoin in a sample. The absorption spectrum data should reveal a characteristic peak at around 670 nm which is indicative of hemozoin absorption. Additionally, SPECTRA is expected to correctly identify the presence or absence of hemozoin in each sample without generating false results.

4. Code

```
# Libraries -----------------------------------------------------

import RPi.GPIO as GPIO
import time
import board
import drivers
from RPLCD.i2c import CharLCD  # Import CharLCD from RPLCD.i2c
import numpy as np
import matplotlib.pyplot as plt
from adafruit_as7341 import AS7341

# Functions -----------------------------------------------------

def setup():  # Function to setup gpio pins and pwm
    global p
    global LedPin
    global StartButton
    global ContButton

    # Initialize lcd instance
    lcd = CharLCD('PCF8574', 0x27)   # LCD i2c address: 0x27

    GPIO.setmode(GPIO.BCM)  # use GPIO Numbering

    LedPin = 18     # define the LedPin (GPIO18)
    StartButton = 5 # define the "Start Test" button (GPIO5)
    ContButton = 6  # define the "Continue" button (GPIO6)

    GPIO.setup(LedPin, GPIO.OUT)     # set LedPin to OUTPUT mode
    GPIO.output(LedPin, GPIO.LOW)    # make ledPin output LOW to start off

    GPIO.setup(StartButton, GPIO.IN) # Set GPIO5 as an input for the "start test" button
    GPIO.setup(ContButton, GPIO.IN)  # Set GPIO6 as an input for the "continue" button

    p = GPIO.PWM(LedPin, 500)        # set PWM Frequence to 500Hz
    p.start(0)                       # set initial Duty Cycle to 0

def wait():  # Function to wait for user to start experiment
    print("Waiting for experiment")                  # print to terminal
    display_on_lcd("WAITING FOR         EXPERIMENT")  # print to lcd
    while True:
        if GPIO.input(StartButton) == GPIO.HIGH:
            lcd.clear()
            break

def wait2():  # Function to wait for user to press “continue” button
    print("Press button to continue")
    display_on_lcd("PRESS BUTTON        TO CONTINUE")
    while True:
        if GPIO.input(ContButton) == GPIO.HIGH:
            lcd.clear()
```

```
            break

def display_on_lcd(data):   # Function for displaying message on LCD
    lcd.clear()             # Clear LCD screen
    lcd.write_string(data)  # Display the desired message

def PWM_calibration():      # Function to calibrate LED brightness
    global setDutyCycle
    setDutyCycle = 100

    display_on_lcd("STARTING PROGRAM     CALIBRATING LED")

    # Start with the initial duty cycle
    p.ChangeDutyCycle(setDutyCycle)

    # Check if all sensor values are below the threshold (to avoid saturation)
    while True:
        measure1 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure2 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure3 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        average = (measure1 + measure2 + measure3)/3

        # Check if all sensor values are below 65535
        if all(value < 65000 for value in average):
            print(average)
            print(setDutyCycle)
            break # Exit the loop if all values are below the threshold

        # Decrease the duty cycle by 1
        setDutyCycle -= 5
        p.ChangeDutyCycle(setDutyCycle)
        print("Changed duty cycle")

    display_on_lcd("CALIBRATION         COMPLETE")

    time.sleep(1.5)

def loop():  # Function to measure absorbance

    while True:
        print("Input calibration solution")
        display_on_lcd("INPUT SOLUTION      FOR CALIBRATION")
        time.sleep(5)
```

```
        print()
        wait2() # wait for "continue" button to be pressed
        print()

        print("Taking base measurement...")
        display_on_lcd("TAKING BASELINE     MEASUREMENT...")

        measure1 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure2 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure3 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure4 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure5 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure6 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        print(measure1)
        print(measure2)
        print(measure3)
        print(measure4)
        print(measure5)
        print(measure6)
        print()

        time.sleep(1)

        print("Input sample")
        display_on_lcd("INPUT SAMPLE")
        time.sleep(5)

        print()
        wait2() # wait for "contiue button to be pressed
        print()

        print("Starting sample measurement...")
        display_on_lcd("STARTING SAMPLE     MEASUREMENT...")
```

```
        measure7 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure8 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure9 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure10 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure11 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        measure12 = np.array([sensor.channel_415nm, sensor.channel_445nm,
sensor.channel_480nm, sensor.channel_515nm, sensor.channel_555nm, sensor.channel_590nm,
sensor.channel_630nm, sensor.channel_680nm])

        print(measure7)
        print(measure8)
        print(measure9)
        print(measure10)
        print(measure11)
        print(measure12)
        print()

        average1 = (measure1 + measure2 + measure3 + measure4 + measure5 + measure6)/6
        average2 = (measure7 + measure8 + measure9 + measure10 + measure11 + measure12)/6
        absorption = average1 - average2


        # Convert arrays to strings with fixed width for each element
        average1_str = ["{:<12.3f}".format(num) for num in average1]
        average2_str = ["{:<12.3f}".format(num) for num in average2]
        absorption_str = ["{:0<10.4f}".format(num) for num in absorption]

        # Print the formatted arrays
        print("Average 1:", " ".join(average1_str))
        print()
        print("Average 2:", " ".join(average2_str))
        print()
        print("Absorption detected:", " ".join(absorption_str))
        print()

        # Create subplots
```

```
        fig, axs = plt.subplots(3,1) # 3 rows, 1 column

        wavelengths = np.array([415, 445, 480, 515, 555, 590, 630, 680])

        # First Subplot
        axs[0].plot(wavelengths, average1, marker='o', linestyle='-')
        axs[0].set_xlabel('Wavelength (nm)')
        axs[0].set_ylabel('Absorption')
        axs[0].set_title("Base Measurement")
        axs[0].grid(True)
        #axs[0].show()

        # Second subplot
        axs[1].plot(wavelengths, average2, marker='o', linestyle='-')
        axs[1].set_xlabel('Wavelength (nm)')
        axs[1].set_ylabel('Absorption')
        axs[1].set_title("Sample Measurement")
        axs[1].grid(True)
        #axs[1].show()

        # Third subplot
        axs[2].plot(wavelengths, absorption, marker='o', linestyle='-')
        axs[2].set_xlabel('Wavelength (nm)')
        axs[2].set_ylabel('Absorption')
        axs[2].set_title("Total Absorption")
        axs[2].grid(True)
        #axs[2].show()

        plt.tight_layout() # Adjust layout to prevent overlap
        plt.show()#block=False)

        if absorption[6] > absorption[7] and absorption[6] > absorption[4] and absorption[6]
> absorption[5] and absorption[6] >= 2000:
            print("Malaria Detected")
            display_on_lcd("MALARIA DETECTED")
        else:
            print("No Malaria Detected")
            display_on_lcd("NO MALARIA          DETECTED")

        time.sleep(2)

        break


def destroy():
    p.stop()       # stop PWM
    GPIO.cleanup() # Release all GPIO
    lcd.clear()    # Clear the LCD screen

# Main Code ------------------------------------------------------------------------------

i2c = board.I2C()       #I2C Address for sensor is 0x39
```

```
sensor = AS7341(i2c)
GPIO.setwarnings(False)

setDutyCycle = 0  # Initialize duty cycle

if __name__ == '__main__':     # Program entrance

    lcd = CharLCD('PCF8574', 0x27)
    setup()  # set up all the GPIO ports

    while True:
        wait()   # wait for user to start experiment

        print ('Program is starting ... ')
        print ("Calibrating SPECTRA")

        PWM_calibration()    # call function to set the correct duty cycle

        print("Calibration complete!")

        time.sleep(2)

        try:
            loop()    # take control and sample measurements

        except KeyboardInterrupt:  # Press ctrl-c to end the program.
            destroy()

        time.sleep(2)
```