



Noninvasive Module for Biomonitoring Live (NIMBL)

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Google's free AI tool, Gemini [3], was utilized to quickly learn and gather widely available conceptual information (used instead of the traditional "Google search"). OpenAI's ChatGPT [11] and Microsoft's Copilot [36] were utilized for the same purpose. The information gathered using these tools was paraphrased, and any sections of the document that significantly utilized information curated by an LLM was cited with an in-text citation. If text generated by AI was explicitly used, it was placed in direct quotes. If a specific prompt led to certain information, it was indicated with a reference to the appropriate appendix; otherwise, assume information was obtained using a wide variety of different prompts where documenting them does not provide practical benefit.

Gemini [3], ChatGPT [11], and Microsoft Copilot [36] were also utilized to help format the reference list to IEEE citation standards.

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2. PROJECT DESCRIPTION

2.1 PROJECT NARRATIVE

2.1.1 Background and Motivation

There are many situations in which simple biomonitoring can save or improve a life. Whether providing important insights in an emergency situation or measuring the vitals of a sleeping baby, blood oxygen levels and heart rate are indicators of potentially serious threats. Our motivation with this project is to build a prototype that has the capability to be scaled down in future iterations to provide an inexpensive vitals monitoring system that could be dynamically included in many different use cases.

2.1.2 Goals and Objectives

The overarching goal of our project is to provide an inexpensive and low-profile device that can provide people with the ability to easily monitor two vital biometrics: their blood oxygen levels and heartbeat. Ultimately, our **goals** are as follows:

Basic

- Offer a safe and accurate noninvasive biomonitoring experience by featuring power element isolation between the electrical systems and the user. We will also radiate within the appropriate bandwidths and at the appropriate power levels for RF communications.

Advanced

- Make the device versatile. By versatile, we mean that the design should be modular in such a way that it could fit onto various mounts and inside of various casings.
- High power efficiency would also contribute to realizing a versatile biomonitor; the longer that the device can operate on a single charge, the better.

Stretch

- Maximize long-term utility and data storage by effectively communicating data to an external base station via RF communications.

From these goals, we can derive the following **objectives**.

Basic

- Isolate power storage and circuit elements from the user
- Accurately measure pulse rate and blood oxygen levels using noninvasive sensing
- Utilizing an on-board processor, leverage software to transform sense data into visualizations: a percentage (for blood oxygen monitoring) and a pulse rate measurement

Advanced

- Total prototype weight under 3kg
- Ensure that the prototype can operate for at least three continuous hours of screen-on time
- Communicate data via RF to a base station for storage

Stretch

- Establish software for processing stored biometric data to generate long-term analyses

2.2 FEATURES, REQUIREMENTS AND STANDARDS

2.2.1 Related Products and Reviews

2.2.1.1 - Owlet Dream Sock®

The Owlet Dream Sock® is designed for newborns and infants. It is a low-profile module that includes a sensor, flexible PCB, and onboard power storage [1]. It measures various biometrics, including heart rate and blood oxygen levels, before broadcasting these results to an external base station using RF. The data is finally processed from the base station to present parents with data regarding the health of their baby (pulse rate, blood oxygen, sleep cycle, etc).

The Dream Sock® is similar to NIMBL in that it measures heart activity and blood oxygen levels and has a strong emphasis on maintaining safety for its users (The Dream Sock® being an FDA-cleared product). One key difference is that the Dream Sock® aims to prioritize an incredibly low weight (<0.15kg) and a flexible profile (139.7mm x 82.6mm x 190.5mm) to optimize specifically for the comfort of babies. While it is still important for our prototype to be light, we aim to keep our prototype systems large for ease of troubleshooting, with an eye towards preserving the possibility of downscaling in future iterations. It is also worth noting that the bulk of the Dream Sock's® processing occurs after its data is transmitted to the base station; there is no display mechanism on the same frame as the sensor module. This is another difference from NIMBL, where we would want an on-board processor to perform the data processing and on-board displays to display the results. This addresses a popular complaint that customers have made regarding the Dream Sock®: that is, they say that the RF communication to its base station is unreliable at times, making it impossible to actually access the data being collected [2].

2.2.1.2 - Fingertip Oximeter: Nonin Onyx® Vantage 9590

Pulse Oximeters are devices dedicated to reading or monitoring pulse rate and blood oxygen saturation level (SpO2). They typically come in three form factors: fingertip, handheld, and wearable, each with different benefits and drawbacks. Fingertip Oximeters clip to the end of the finger and utilize spectrophotometry to identify the concentration of oxygenated and deoxygenated hemoglobin based on the absorption of different wavelengths of EM radiation, as well as the pulses of absorption rates (changes in arterial flow) to characterize heart rate. Fingertip Oximeters are typically more affordable than the other options; they are highly portable due to their small size, simple to use, provide fast readings, and are suitable for quick checks. However, they are not for constant monitoring; often do not include features such as data logging, smartphone apps, and alarms; and they can be susceptible to inaccuracies from movement or even skin tone [3].

The Nonin Onyx® Vantage 9590 Fingertip Oximeter is regarded as the “Gold Standard” for this form factor [3]. A study published in *eBiomedicine* concluded that this device

was one of the two best performing devices for error related to skin pigmentation [4]. The Vantage 9590 utilizes a transmissive configuration where LEDs shine 660 nm wavelength red light and 910 nm infrared light [5] through the finger to a photodetector. This configuration makes measurements less sensitive to placement as well as more stable and repeatable [6]. The photodetector captures the waveform produced by the changes in light due to the pulse of the wearer, and passes it off to a digital signal processor (DSP) to filter the signal. Then the DSP uses an algorithm to detect pulse signals [3]. It is implied that there is an algorithm to calculate the SpO₂ as well. The device also leverages another algorithm that allows for a variable averaging time so that the device can still provide a fast 3-second reading (or faster), or extend the reading if the signal is inconsistent or weak, maintaining device accuracy [7]. The numerical pulse and SpO₂ measurements are displayed using 7 segment LEDs and a tricolor LED indicates pulse quality [8]. The device is powered by two AA batteries [5].

2.2.1.3 - Handheld Oximeter: Masimo Rad-G®

Handheld Oximeters can offer more accuracy over Fingertip Oximeters, as well as greater versatility if they utilize probes that can attach to other areas of the body than the finger. They can often include additional features due to their larger form factor, and are typically more robust. The Masimo Rad-G® is a handheld pulse oximeter that was designed to be durable enough to survive 6 ft drops onto hard surfaces. It is able to interface with various sensor probes so it can be used in various situations. The Rad-G® measures SpO₂ and pulse rate just like the Vantage 9590. The handheld is also engineered with additional features; it displays the Plethysmograph (the PG in PPG) waveform on its screen as well as the Perfusion Index (PI), the Respiration Rate, and the Plethysmograph Variability Index (PVI) [9]. PI is a parameter that represents the strength of the pulses of blood flow at the sensor. This PI value is useful for determining shock or other circulatory issues in a patient. The PVI is an indicator of a patient's fluid responsiveness to determine if additional fluids will benefit a patient's circulation. The PVI can be obtained noninvasively. Finally, the Respiration Rate measurement allows users to monitor a patient's breathing through fluctuations in the Plethysmograph. This reduces the amount of equipment the user would otherwise need [3]. It has a 2.8" (diagonal) color LCD display and is powered by a rechargeable Lithium ion battery. It is capable of storing data measurements for 96 hours [9].

2.2.1.4 - Wearable Oximeter: Withings ScanWatch 2

Wearable Oximeters benefit over the other form factors because they are more suited for continuous monitoring and data logging. However, they can be less accurate due to motion and varying contact conditions. ScanWatch2 is an example of a Wearable Oximeter. It is designed to look and function like a watch. It uses a Multi-wavelength PPG with 16 channels to improve monitoring accuracy of SpO₂ and pulse rate. It supports many additional features: temperature tracking, AFib detection, sleep quality measurements, breathing quality measurements, accelerometer, altimeter, smart watch features, the ability to connect to other biomonitoring devices, and more [10]. Unlike the Fingertip Oximeter and Handheld Oximeter examples, the ScanWatch 2 uses a reflective configuration for the PPG sensor, meaning the photodetector is on the same plane as the LEDs and measures the amount of light reflected. This configuration allows the sensor to

be used on other parts of the body where a transmissive PPG could not be [6]. The watch also has an OLED screen to display information and is charged using a docking station. It is capable of storing health data for 7 days locally, or unlimited storage in the cloud [10].

2.2.1.5 - Related Products' Features Applied to NIMBL's Features

From our research on other products, there are a few features that have been applied to our project. The robustness and rechargeable battery from the Masimo Rad-G® were clear additions to bring. We took inspiration from the simplicity of the Nonin Onyx® Vantage 9590's display and chose to use a simplistic LCD screen for the same type of display. Having an LCD display enables the flexibility of displaying text in a budget-friendly manner. From the DreamSock®, we would like to preserve the transmission of data via RF to a base station for storage and potentially further processing. We will likely utilize a PPG sensor to obtain vitals information since they work well for a cursory measurement and present lower risk than electrodes. Our choice in the PPG sensor is inspired by the ScanWatch 2 so our device can be used in various different applications.

2.2.2 Features and Functionality

We have highlighted key features in pursuit of reading two vital biometrics. The project's main feature is the biometric sensor module (likely PPG). This will be placed in an easy-to-access location where a user can hold their finger up to the scanner. As we read a user's biometric data, the MCU will run an algorithm that filters the noise to ensure an accurate reading is displayed. A custom 3D-printed enclosure will house the electronics, providing an aesthetic shell as well as protecting the parts from environmental factors and physical damage. Additionally, a micro-USB port is placed on the back for easy charging. Users do not have to worry about overcharging or shorting the battery, as protection circuits will be designed. On top of the enclosure will be a singular LCD screen that will show the readings of heart rate and blood oxygen levels. The displayed values will be continuously updated as the user keeps their finger on the sensor. Near the sensor module, we will also include an on-off switch so the user can save battery life when the product is not in use. The MCU will also put the device into a sleep mode if no finger is detected on the sensors after 10 seconds.

2.3 KEY ENGINEERING SPECIFICATIONS

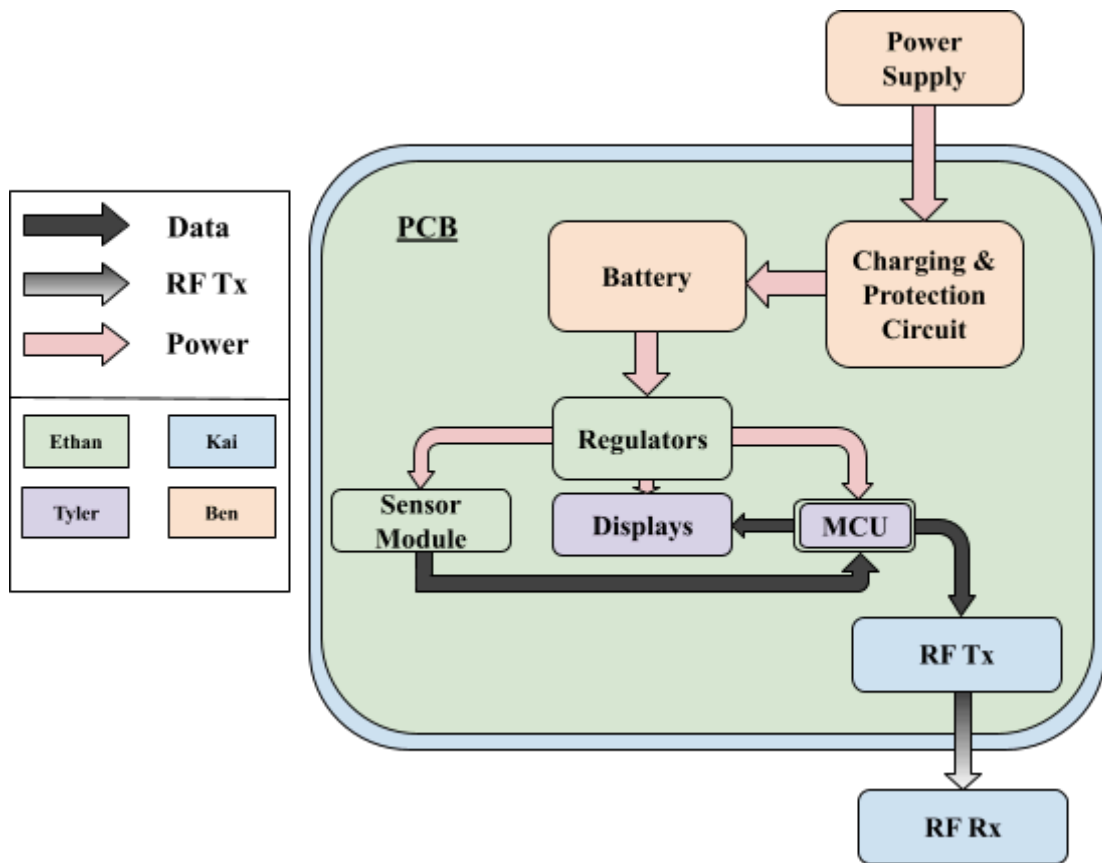
2.3.1 Overall System Specifications

Marketing Requirements	Engineering Requirements	Justification
2,3	<i>Pulse rate</i> should be obtained <i>within 10 seconds</i> of contact.	There could be noise as we read data, so this time frame should give us an accurate measurement with fast responses.
4	<i>Screen-on time</i> should be ≥ 3 <i>hours</i> .	Users should be able to read vital information for a long time without frequent charges.
1	We must <i>transmit</i> a <i>maximum of 36dBm EIRP</i> .	Compliance with FCC regulations (Part 15.247) on RF communications.
1	We must <i>transmit between 902-928MHz</i> .	Compliance with FCC regulations (Part 15.247) on RF communications.
5	<i>Wireless transmission</i> should be successfully received from <i>at least 10 meters away</i> .	Being able to save data via wireless communication allows for further analysis of health patterns.
Marketing Requirements 1. The prototype must be safe and compliant. 2. The prototype should provide accurate measurements of blood oxygen and pulse rate. 3. The prototype should respond quickly. 4. The prototype should have good battery life. 5. The prototype should maximize long-term utility and data storage options if possible.		

2.3.2 Subsystem Specifications

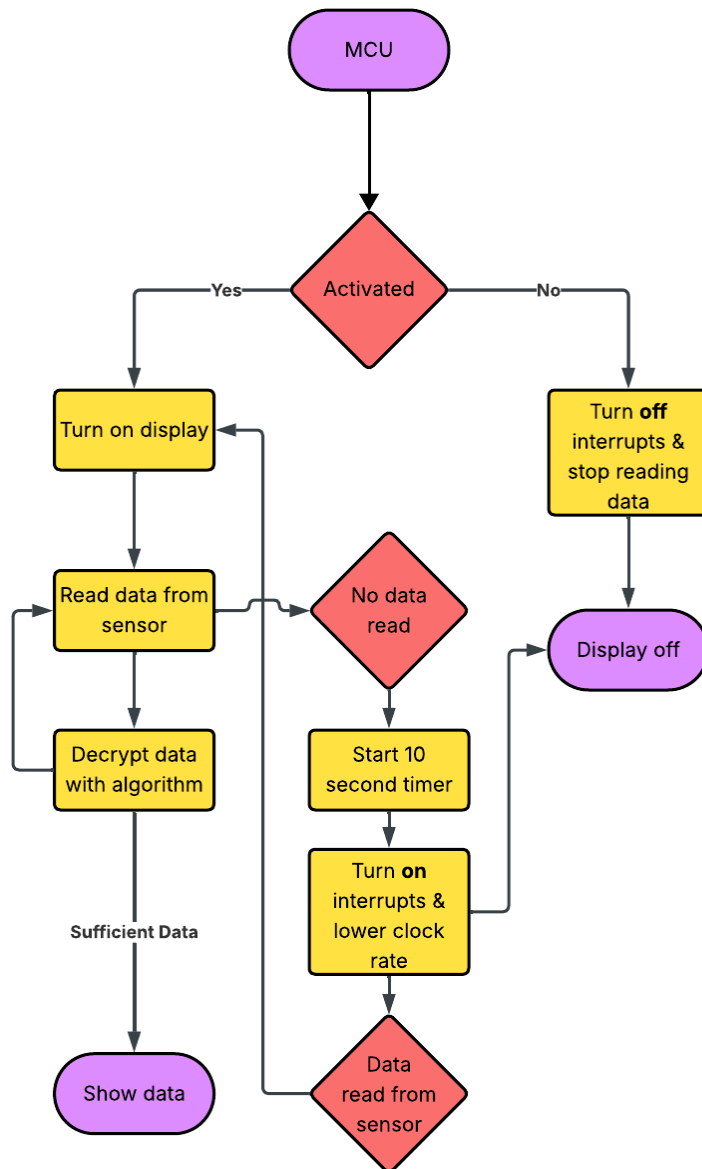
Subsystem	Parameter	Specification
Power	ACDC Conversion	DC Output
Power	DC Power	< 10W
Power	Battery Type	Lithium Ion
Power	Charge Port Interface	Micro-USB
Power	Nominal Battery Voltage	3.7V
Power	Maximum Battery Output Power	< 10W
Power	Regulator Voltages	3.3V & 5V
Power	Shut-Off Temperature	$\leq 60^{\circ}\text{C}$
Sensor	Sensor Type	PPG
Sensor	Minimum Sensor Sampling Interval	$\leq 1\text{s}$
Sensor	Sensor Communication Protocol	SPI
Software/Hardware	MCU Clock Speed	16MHz
Software/Hardware	MCU Programming Language	C
Software/Hardware	Display Type	LCD
Software/Hardware	Initial Data Display Time	$\leq 10\text{s}$
RF	Transmission Distance	$\geq 10\text{m}$
RF	EIRP	$\leq 36\text{dBm}$
RF	Operating Frequency	902-928MHz
Sensor	Contact Time Before Thermal Injury	>8 hours

2.4 HARDWARE BLOCK DIAGRAM

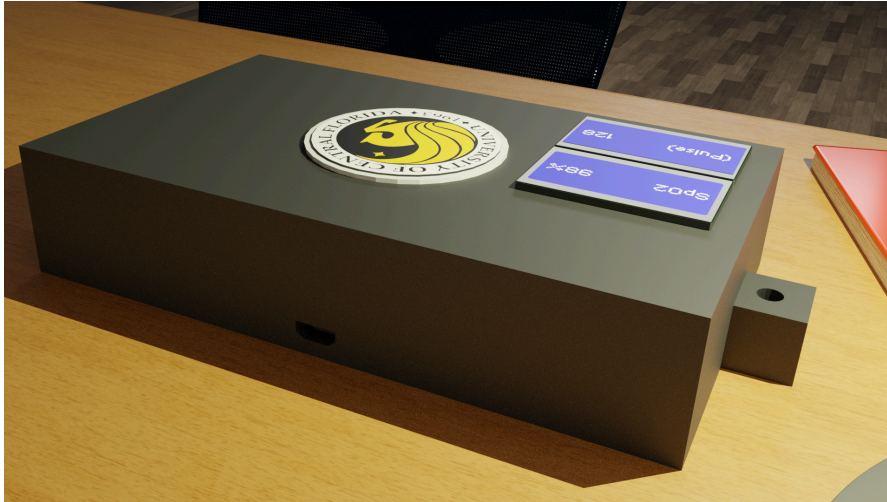


2.5 SOFTWARE FLOWCHART

Tyler Takimoto will be responsible for the software development. Kai Ford will assist with providing necessary algorithms.



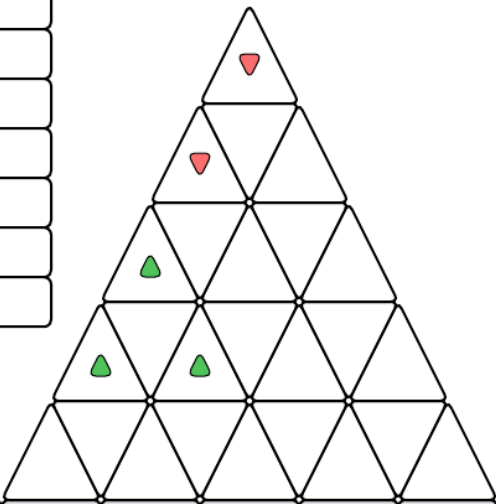
2.6 PROTOTYPE ILLUSTRATION



2.7 BUDGETING EVALUATION

2.7.1 House of Quality

Symbol	Description
	Positive Correlation
	Strong Positive Correlation
	Negative Correlation
	Strong Negative Correlation
+	Positive Polarity
-	Negative Polarity

Engineering Requirements						
		Battery Life	Overheating Protection	Overcharging Protection	Reading Interval	Wireless Comm. Distance
Marketing Requirements		+	+	+	-	+
Battery Life	+					
Latency	-					
Safety	+					
Accuracy	+					

2.7.2 Estimated Costs Table

Subsystem	Component(s)	Cost
Power	Power Supply	\$20
Power	Battery	\$20
Power	Battery Circuitry	\$25
Power	Regulator Circuitry	\$25
Sensor	Sensor	\$10
Sensor	Sensor Circuitry	\$25
Software/Hardware	MCU	\$5
Software/Hardware	Screen	\$15
RF	RF Module + Antenna	\$80
RF	RF Circuitry	\$25
General	Shipping	\$50
General	Tools + Supplies	\$30
	TOTAL	=\$330

2.7.3 Preliminary Budget Allocation Table

Student	Allocation
Kai Ford	\$82.50
Tyler Takimoto	\$82.50
Benjamin Will	\$82.50
Ethan Denner	\$82.50
TOTAL	=\$330

3. RESEARCH AND INVESTIGATION

3.1 HARDWARE COMPARISON AND SELECTION

3.1.1 Technology Comparison and Selection (Hardware)

3.1.1.1 Reflective PPG Sensor Technology Comparison and Selection

PPG is an acronym for Photoplethysmography, which is a technique used to detect changes in the blood volume in the microvascular bed of tissues by leveraging fundamentals of spectrophotometry [12]. In simpler terms, light is directed through the skin of an individual, and a sensor measures how much of the light was absorbed by the tissue, transmitted to the sensor, or both. Specifically, the theoretical underpinning to the PPG sensor is a modified version of the Beer-Lambert Law [12], [13]. The Beer-Lambert Law explains the exponential attenuation of light as it passes through a medium is determined by the attenuation coefficient of the material, the path length of the light, and the concentration of scattering and absorbing particles [12], [14]. The law is modified to account for the complexities involving light interacting with tissue [12], [13]. In the case of the PPG sensor, the important absorbing particle is Hemoglobin.

Hemoglobin is a protein found in red blood cells, and it is responsible for carrying oxygen throughout the circulatory system. Beneficially, Hemoglobin also selectively absorbs light. Thus, the light absorption of the PPG sensor varies with the amount of blood passing through the tissue, which is synchronous with the cardiac cycle [14]. The measurement of the fluctuations of the blood volume of tissue using light allows the PPG sensor to derive a waveform that contains physiological information about the patient, such as pulse rate, oxygen saturation in the blood, etc. This waveform consists of an AC (alternating current) component and a DC (direct current) component [12]. The DC signal is produced by the non-pulsatile parts of the body that maintain relatively constant volume or optical characteristics with each heartbeat, such as bone, skin, the baseline volume of blood in the arteries, and venous blood since its pulsatile events are too small to be measured by the PPG [12], [15]. The magnitude of the AC swing of the signal is typically less than one percent of the magnitude of the DC component, and this swing is produced by the dynamic changes in the volume of blood flowing through the arteries with each beat of the patient's heart [12], [15]. Though, the timing of the pulse read by the PPG is not perfectly aligned with the patient's heartbeat [12]. The AC component contains the information the PPG sensor is looking for, so to monitor these small fluctuations in light intensity, the device utilizing the sensor constantly performs a zero calibration to keep its baseline stable [16].

The PPG sensor comes in two general forms: transmissive and reflective. In the transmissive configuration, the light source and the sensor are on opposite sides of the body part the device is attached to. The reflective configuration has the light source and detector on the same side of the body part, allowing it to be used in more locations on the body. While the transmissive configuration is more accurate due to the more stable positioning its form factor allows, the versatility of the reflective configuration more

appropriately fits the scope and goal of this project. Therefore, this project will utilize a reflective PPG sensor, which are available in three discrete categories: Dual Wavelength, Triple Wavelength, and Multi-Wavelength sensors.

3.1.1.1.1 Dual Wavelength Reflective PPG Sensor

Different wavelengths of light are able to penetrate tissues at different depths [12]. Shorter wavelengths like blue and green tend to be absorbed more and penetrate a shorter distance to the superficial capillary beds [12], [15], [17]. Longer wavelengths like red and infrared are able deeper to the arterioles and arteries [12]. Another important fact for the choice of wavelengths used by a PPG is that oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin have different light absorption characteristics (Hb) at different wavelengths [18]. Hb is able to absorb less infrared light and more red light while HbO_2 is able to absorb more infrared and less red [18]. This is why the Dual Wavelength Reflective PPG sensor typically uses red light (about 660 nm) and infrared (about 940 nm); the fluctuation in the AC signal occurs at both wavelengths indicating a pulse, but the amplitude of the fluctuation differs for the two wavelengths due to the concentrations of Hb and HbO_2 in the blood, allowing an algorithm to calculate the blood oxygen saturation (SpO_2) level [19]. In addition to SpO_2 and pulse, the Dual Wavelength PPG sensor is able to also detect Perfusion Index, the strength of the blood flow at the sensor site, and Respiratory Rate through changes in overall blood volume due to breathing [20], [21].

The structure of the Reflective PPG sensor is better described as a complete system [22]. LEDs are used to illuminate the skin and a detector, typically in the form of a photodiode, which converts the intensity of the reflected light into nano-ampere current [15]. This weak current is fed into a Transimpedance Amplifier, which converts it to a measurable voltage [15], [23]. Since the DC component of the signal is orders of magnitude larger than the AC component, an MCU feeds a signal to a DAC, which outputs a current offset to reduce the large DC component to avoid oversaturating the Transimpedance Amplifier [23], [24]. After the Transimpedance Amplifier, the signal is fed to a Programmable Gain Amplifier to adjust gain based on the signal strength [15]. Then the signal is fed to an ADC so it can be processed by the MCU [15], [25]. The MCU is also responsible for pulsing the LEDs sequentially to monitor the absorption of each wavelength independently without one corrupting the other's data [26]. The pulsing characteristics of the LEDs introduce tradeoffs between power consumption and device accuracy [15], [27]. An accelerometer can also be used to provide a motion reference signal to estimate noise produced by movement and use advanced DSP techniques to remove the noise from the PPG's signal [17]. This system can be constructed from discrete components, however, the complexities of managing the noise and accuracy for the extremely small signals means it is more beneficial and within the scope of this project to utilize specialized ICs that integrate many of these components [24]. Also, using an IC will significantly improve the performance of the device being created for this project [24]. A final important part of the system is the sensor to skin contact. A solution in the mechanical design of the sensor or the sensor mount needs to be incorporated to avoid too little or too much pressure being applied to the tissue, which can cause inaccuracies

[17], [28]. Though, the ideal pressure varies widely from 30 to 113 mmHg based on gender, age, skin elasticity, and blood vessel structure [17].

Before processing, a band-pass filter is utilized to isolate the frequencies corresponding to cardiac rhythm, which is between 0.5 Hz and 6 Hz [29]. This helps filter out low frequency noises from thermoregulation and other body functions, and high-frequency noise from electrical interference and ambient light [17], [19]. Also, the signals from the different wavelengths are normalized to a common scale for consistent calculations [19].

To identify the heart rate of a patient the fundamental frequency of the AC signal is identified using techniques like the Fast Fourier Transform or the MUSIC algorithm [3]. To calculate the SpO₂ of a patient, an algorithm separates the AC and DC components of the signal and calculates the ratio of the AC to the DC signals [30]. This ratio is called the modulation ratio [15]. The higher the ratio, the stronger the pulse and the greater the absorption by the arteries [19]. Next the ratio of ratios, also known as the R-value is calculated. The R-value is the ratio of the red modulation ratio to the infrared [15], [30]. An empirically derived calibration curve is then used to find the final SpO₂ percentage [15], [30]. This curve is device specific and is typically provided by manufacturers [15], [30]. Calculating Perfusion Index is simply the ratio of the AC to DC component expressed as a percentage. A stronger Perfusion Index indicates stronger blood flow and, therefore, a more accurate SpO₂ reading [20]. A PPG can detect respiratory rate because inhalation reduces left ventricular filling and stroke volume in the heart, which leads to a lower pulse pressure and thus a reduced PPG signal amplitude [21]. Various methods for detecting this are outlined in [21]; however, detecting the Respiratory Rate using these methods is challenging (reliable methods are still a research topic) and most likely out of scope for this project.

3.1.1.1.2 Triple Wavelength Reflective PPG Sensor

The Triple Wavelength Reflective PPG Sensor has a similar function and structure as the Dual Wavelength PPG except for the additional green wavelength of light the sensor uses. This green light source is typically of the wavelength of 520-580 nm [31], [32]. The green light in a PPG has a higher signal-to-noise ratio (in other words, a higher AC to DC ratio) than that of its red and infrared counterparts, and this results in a more accurate pulse measurement [33]. Studies find the green PPG signal aligns closely enough with a patient's ECG signal that it can be used to calculate Pulse Rate Variability accurately without the need of the additional ECG sensor [34].

A major cause of green's improved signal-to-noise ratio is the fact that the shorter wavelength of green does not penetrate as far as red or infrared [32], [33]. Green cannot penetrate deeper than 0.6 mm into human tissue whereas red and infrared can penetrate 0.8 to 1.5 mm into tissue [32]. This shallow penetration depth means green does not detect as many non-pulsatile components as the red and infrared wavelengths do, resulting in a higher AC to DC ratio in the measured signal [33]. Also, green is absorbed more by hemoglobin than red and infrared leading to a clearer signal [34]. The problem with green, though, is that the absorption characteristics of HbO₂ and Hb do not differ significantly enough for green light, meaning it cannot be used for SpO₂ calculation,

hence the need to still use red and infrared in the sensor [35]. Also, the penetration depth is too shallow to read the same physical phenomenon that the red and infrared signals measure; specifically, the voluminous blood flow in the arteries. This results in a discrepancy: the green is more accurate at detecting pulse despite not being able to detect changes in blood volume in the arteries, the most significant indicator for pulse in the Dual Wavelength PPG. The truth is, the exact underpinnings of what a PPG sensor measures with any wavelength is still a subject of research [32].

The standard model of what the PPG sensor measures was described for the Dual Wavelength PPG. One of the many other models [36] that attempt to rectify the signal discrepancy observed for the green wavelength is outlined in [32]. This model also stresses the importance of optimal contact pressure between the tissue and the sensor. Since the green light can only penetrate reliably to the depths of the capillaries, which are incompressible and cannot pulsate with the heartbeat, [32] proposes that the heartbeat alters the density of capillaries at the sensor site, creating the pulsatile signal. This happens because volume changes in the arteries with each pulse causes the artery to expand, pushing on the surrounding tissue. If the top layer of tissue is inelastic or sufficiently compressed by the sensor, the expanding artery will push more capillaries toward the sensor, increasing capillary density at the site and thus increasing the amount of green light absorbed [32]. This means the green wavelength produces an AC signal that originates mainly from one source, the mechanical fluctuations created by the pulse, and is less interfered with by other frequencies of noise produced by the body that the deeper penetrating wavelengths are susceptible to, such as motion artifacts or thermoregulation [32]. So, the biggest benefit of utilizing the green wavelength is as a stable pulse reference point to compare the red/infrared signals to for improved accuracy of measurements.

Fusing all three wavelengths makes the Triple Wavelength PPG much more resilient to skin tone and motion artifacts than the Dual Wavelength PPG [37]. To do this, the algorithm controlling the signal processing must identify the wavelengths with the highest signal-to-noise ratio [3], [38]. In most cases this will be green which is already much more impervious to sources of noise such as motion; and the less noisy signal will be used as the authoritative pulse rate [39]. Green is heavily attenuated by dark skin tones and tattoos though [40]. In cases where there is heavy attenuation of the signal, the algorithm should identify two wavelength channels that agree on pulse rate to be used as the authoritative rate [3]. Since the red and infrared are less absorbed by darker skin, at least one of them should have a similar enough measurement to the green to identify the pulse rate clearly. Dynamic LED brightness is also another solution to the increased attenuation from tattoos and dark skin. However, if all three channels do not agree on a pulse rate, the algorithm should assign weights to the channels based on their signal-to-noise ratios and their waveform likeness to a pulse (the weights signify confidence in the channels' heart rate measurements), and feed them through filters such as a Kalman, Alpha-Beta, etc. to smooth the results and obtain a reliable measurement [3], [41]. After obtaining reliable measurements from either of the methods, Pulse Rate Variability can be calculated. Pulse Rate Variability is the measurement of the time intervals between sequential heartbeats, which can be used as an indicator for various

health conditions. Pulse Rate Variability can be identified by the standard deviation of intervals or the root mean square of successive differences in the time domain, or in the frequency domain by observing power fluctuations in the low and high frequency bands in the spectrum [42], [43].

3.1.1.1.3 Multi-Wavelength Reflective PPG Sensor

The Multi-Wavelength Reflective PPG Sensor is a Triple Wavelength PPG with any number of additional wavelengths added to the device. Typically, amber/yellow, blue, secondary red/infrared, and a long wavelength infrared wavelength are the additional wavelengths used for additional channels [3]. The added bands expand the capabilities of the sensor to be useful for advanced research and clinical applications, while also improving the accuracy of the sensor.

Yellow/amber light penetrates deeper into tissue than green light, but penetrates more superficially than red [44], [45]. This positions yellow/amber as a middle ground between green and red, balancing the benefits and drawbacks of each, as well as providing the multi-wavelength PPG the capability to more finely measure blood volume changes at specific tissue depths [45]. First, the issue that plagues all wavelength PPGs is that melanin, a natural pigment in skin, absorbs light ranging from 350-1200 nm [46]. A seemingly simple fix to this would be to design a sensor that uses light outside of that range; however, water absorbs wavelengths of light above 1000 nm and below 300 nm strongly [47]. This water absorption characteristic forces PPGs to operate within the melanin absorption band. Different people have different levels of melanin, resulting in various conditions of signal quality and attenuation. So, a common engineering challenge when designing devices that utilize PPG sensors is maintaining accuracy of the device for different patients across skin tones. As discussed previously, green wavelength light can offer superior signal quality and pulse rate measurements due to its penetration depth. On the other hand, green is strongly attenuated by melanin. Since melanin absorbs less light as wavelength increases and yellow penetrates tissue similarly to green, using a yellow light channel allows for a high quality signal that is less sensitive to melanin [48], [49].

A more specific description of tissue penetration depth ranging from superficial to deep is: blue penetrates to the papillary capillaries in the epidermis, green penetrates shallowly into the dermis to reach the dermal plexus, yellow is able to penetrate deeper in the dermis and thus can reach the branches of the arteries called the arterioles, and red/IR penetrates past the dermis to the arteries. Simply put, each wavelength category penetrates to a unique structure under the skin. The total time difference from the red/IR and blue PPG signals is the Pulse Transit Time (PTT) [45]. PTT can be used as an index for blood pressure estimation and arterial stiffness [44]. Yellow/amber light is useful for this because the specific PTT from wavelength to wavelength (tissue layer to tissue layer) can be associated with specific arterial wall characteristics [45].

The utilization of blue wavelength light in PPG sensors is still under research just like with yellow, and thus not many sources exist to provide information regarding its benefits and drawbacks compared to the other wavelengths. [50], a study published in 2021, was only able to find two sources comparing blue light and the other wavelengths. These two

sources are [51] and [39] in this project's reference list (see Appendix ...). Other sources in this reference list use or briefly mention blue light, but none really give any significant comparison between the wavelengths other than [44]. However, [44] only identifies that blue light measurements are unaffected by a blood pressure cuff, information which is not applicable to this project. In [39] and [51], it was found that green light is far better for measuring Heart Rate than blue. Source [50] notes that there may have been some bias in those findings due to their experimental setups, but concluded in their study that green and blue light have no significant accuracy difference, and therefore, can be used interchangeably. The reason for this is most likely due to the similar penetration depth between green and blue light [45]. Melanin strongly absorbs blue light, leading to a shallower penetration depth than green. Hb and HbO₂ are also more strongly absorbed by blue than green [46], implying that blue is more sensitive to pulsatile changes in blood volume than green. Therefore, blue light's weak penetration depth is counterbalanced by its strong hemoglobin absorption. Blue light does have additional capabilities as treatment for various conditions, so it could be used in place of green light (or with it) to serve both as a PPG sensor and therapy for medical issues [50]. However, treatment of ailments is well outside this project's scope and expertise, so these advanced capabilities will not be discussed.

The final two wavelengths used for additional channels are a secondary red/infrared wavelength and a long wavelength infrared channel. These two wavelength ranges are best suited for really advanced capabilities. First, the secondary red/infrared wavelength can be used to improve the accuracy and robustness of the standard PPG measurement. This additional channel helps reduce common sources of interference like temperature, melanin concentration, and perfusion conditions by providing an algorithm more data to compute or a neural network more data to train on [52]. Additionally, this extra channel can be used in conjunction with a wide range of different wavelengths like long wavelength infrared to measure dyshemoglobins, such as carboxyhemoglobin and methemoglobin. These dyshemoglobins can be sources of error in standard pulse oximetry measurements, or indications of health issues like carbon monoxide poisoning [53], [54]. Many other advanced capabilities are possible, for instance cerebral oximetry [55] and tissue hydration monitoring [56], but they require specific PPG device designs or over-complicate the scope of this project, so they will not be discussed further.

3.1.1.1.4 Reflective PPG Sensor Technology Selection and Reasoning

The Triple Wavelength PPG sensor is the best option for this project. It maintains design simplicity, while also improving accuracy of measurements. Accuracy is important as many other inaccuracies of the PPG's measurements may be caused by other design constraints resulting from the nature of this project. Plus, if using all three wavelengths proves to be too difficult/time-consuming, the project can always default to simply utilizing the red and infrared wavelengths on the sensor. A multi-wavelength sensor is just too complex for this project to feasibly utilize, and purchasing any sensor with the additional wavelengths would just be extra cost. The green wavelength still provides the project the opportunity to pursue advanced measurements like Pulse Rate Variability if time permits it.

3.1.1.2 Reflective PPG Sensor Comparison Table

	<u>Technology</u>		
	Dual Wavelength	Triple Wavelength	Multi-Wavelength
Wavelengths	Red (~660 nm) IR (~880-940 nm)	Red (~660 nm) IR (~880-940 nm) Green (~525-540 nm)	Red (~660 nm) IR (~880-940 nm) Green (~525-540 nm) Amber/Yellow and/or Blue and/or Long Wavelength IR and/or Secondary Red/IR (~570-600, 465-480, 970-greater, 730-810 nm respectively)
Capabilities	SpO ₂ Pulse Perfusion Index Respiratory Rate	SpO ₂ Pulse Perfusion Index Respiratory Rate Pulse Rate Variability	SpO ₂ Pulse Perfusion Index Respiratory Rate Pulse Rate Variability Advanced tissue metrics specific to chosen additional wavelengths
Design Complexity	Lowest	Moderate to high	High
Typical Use Cases	Stationary and low-power devices	Wearables and other devices used in dynamic environments	Research and clinical environments
Pros	Lower Power Consumption Simpler Implementation Simpler Signal Processing Smaller BOM Small cost (generally)	Motion-robust Better performance for different skin tones More Capability Manageable complexity and power constraints	Advanced/customizable capabilities Research/clinical-grade accuracy Highest robustness across skin tones, motion, and perfusion levels
Cons	Susceptible to motion Susceptible to skin tones Lower accuracy in low-perfusion conditions Less versatility	More complex firmware required Increased design complexity	Highest complexity Highest cost Largest BOM Highest power consumption
Decision:	Triple Wavelength	Reasoning:	Higher accuracy &

			noise resistant
			Feasibility

3.1.1.3 Display Technology Comparison and Selection

Various display technologies exist for usage on electrical devices. Each type of display has their strengths, weaknesses, and purposes that will be best suited for different scenarios. Some categories to consider when choosing a display would be the following: size, complexity of information, brightness, life span, cost, power consumption, and viewing angle. This section will cover various display technologies, such as LCD and OLED, and determine the best fit for our project. Our goals are to display a small amount of numerical data for a low cost; therefore the display must be able to fit those requirements.

3.1.1.3.1 Segmented & Dot-Matrix

There are a few categories that we must explore to determine the best-fit screen for our application. One important field is the structure of the display. More specifically, we must determine between a segmented or a dot-matrix display.

A segmented screen features pre-designed patterns that are typically used for numeric digits, such as in a digital clock [57]. More applications of the segmented display are: digital watches, calculators, utility meters, medical devices, and appliance displays [57]. These segments can be individually controlled by the processor to create symbols, but are limited by their placement. Usually, these segments can be seen in an “8” pattern, which can show all digits and a large amount of the alphabet. These type of displays can be manufactured to show specific symbols, such as strength of wifi connection and battery indicators, however that can cost extra based on the application and if a special symbol is needed [57]. Despite their flaws, these segmented screens draw very little power as we only need to drive voltage to a few segments at one time, consuming micro-amperes of current [57]. To specify which part of the display to turn on, for a segmented LCD, an AC signal needs to be applied to the desired segment. Typically, there are two ways to provide power to each segment: static drive and multiplex drive. Static drive is when each segment has its own pin that can receive power. Multiplex drive is when segments share pins and a “common” pin controls which segment in the shared pins outputs an image to the screen. Overall, segmented displays have limited options in what they can show but draw less power in return.

Another form of display is called the dot-matrix. This is one of the most common display types. Instead of having individual segments to control, the dot-matrix has a “grid of individual dots, or pixels, arranged in rows and columns”. These pixels are extremely tiny and packed close to each other, allowing creative freedom in what is shown. Any kind of number, letter, graphic, or symbol can be shown. The only limitation is the size of the grid provided. Typically these are used in phone displays, computer monitors, and even vending machines [57]. However, the ability to show just about anything comes with several drawbacks. To display images, a memory-map of all pixels is needed to know

what is being shown and where. Additionally, the entire grid needs to be refreshed constantly to ensure a constant and accurate display. This causes the dot-matrix grid to draw milli-amperes of current, a thousand times more than the segmented display [57].

Out of these two options, it is clear which one fits the goals of our project the best. While the freedom to display anything is great with the dot-matrix display, the device will only need to show numeric data. To keep costs lower, draw less power, and show the information we need, a segmented display is ideal for this project scope. There is one potential issue, showing the difference in both SpO₂ and pulse when we only have numbers to show. This can be solved by having words on the device itself that can label what the numbers mean.

3.1.1.3.2 Passive & Active Matrix

When maintaining the state of the screen, there are two main technologies that are shared between LCD and OLED. These are known as Passive Matrix and Active Matrix. A passive matrix display addresses each pixel directly and “must retain their state between screen refreshes without a benefit of a steady electrical charge” [120]. Since this type doesn’t need a steady electrical charge, it is used when “power consumption has to be reduced, since less backlight is needed” [120]. On the other hand, active matrix displays use Thin Film Transistors (TFTs) with either a switch or capacitor at each pixel that maintains its state [b-Tyler, c-Tyler]. This method is usually seen on larger screens where a passive matrix display would utilize more power. The reason we have Thin Film Transistors to make an active-matrix display is because the passive-matrix displays have an issue when addressing individual pixels. Since the TFTs can address each pixel individually, there is a greater amount of control that can happen per pixel. However, when passive matrix displays are used to address pixels, an “... issue of crosstalk between neighboring pixels” presents itself [122]. If a display requires accuracy where pixels cannot be affected by their neighbors, an active matrix is necessary. Passive matrix displays get this issue from their design, which is “... a crossbar array that crosses horizontally and vertically” [122]. Despite this issue, “passive matrix LCDs do not suffer from crosstalk due to their low resolution” [123]. This issue of crosstalk emerges when we get larger displays that require large pixel counts. The large displays enable “parasitic capacitance between digital signal lines and common electrodes” which cause the crosstalk to occur [123]. Since the project doesn’t plan on using a large, TV-sized display, the passive matrix is ideal due to the simplicity of design.

3.1.1.3.3 Liquid Crystal Display

One of the major, and common display technologies is the LCD, short for Liquid Crystal Display. LCDs are known as non-emissive displays, which means that the method for showing an image, being the crystals, do not themselves emit light. To show an image, “a backlight unit is usually needed”, except for reflective displays. [124]. LCDs are typically seen in four different forms, each accomplishing the same goals in different ways. The first of these is known as the Twisted Nematic Mode. With this mode, the crystals twist 90 degrees either horizontally or vertically to either hide / show the image. Specifically, the “LC director twists 90 degrees continually from the top to bottom substrates” [124]. This introduces a polarization effect which causes the hiding or showing of the display.

These types of displays have a low operational voltage and limited viewing angle, making them seen typically in wristwatches and laptops. Another LCD technology is the Vertical Alignment Mode, or multi-domain VA for better viewing angles. Contrasting the previous method, the crystals in here are vertical when this display is off and closer to horizontal when showing images. This is achieved when an “electric field is in the longitudinal direction” and an “LC with negative delta epsilon” [124]. When a voltage signal is provided, the crystals “gradually tilt” so light passes through [124]. A common use for this technology are televisions and curved displays since VA mode allows for a slight curve. One type of LCD that allows for touch displays is IPS mode. In-Plane Switching makes LC directors “homogeneously aligned” and “electric fields are in the lateral direction” [124]. This disables the ripple effect that can be seen on typical LCD screens when pressing the panel. For that reason, a device that uses touch displays can typically be seen with an IPS display. The final LCD technology we will look at is FFS mode, or Fringe-Field Switching mode. This display was proposed in 1998, featuring “high transmittance, high viewing angle, weak color shift, built-in storage capacitance, and robustness to touch pressure” [124]. This kind of display seems to have everything going for it, having a ton of neat features that the other technologies don’t have. For the most part, this display is used for touch applications since it has a similar “principle with IPS” while also reducing the dead zone areas due to a smaller electrode with and gap [124]. Looking over these four options, two stick out the most. Those being TN and FFS. Twisted Nematic Mode mode has low operational voltage and a low cost, since it is the oldest of the four modes, “first invented in 1971” [124]. Fringe-Field Switching has plenty of quality features that improve user experience, but is usually meant for touch applications. As our project scope doesn’t include a touch display, Twisted Nematic Mode would be ideal to choose from due to a lower cost and low power consumption if LCD becomes the display of choice.

3.1.1.3.4 Organic Light Emitting Diode

Another major player in the display field is the OLED, known as Organic Light Emitting Diode. This type of display is emissive, no backlight is required to show an image. A typical OLED is constructed by “organic stacks sandwiched between anode and cathode” where “electrons and holes are injected from electrodes to organic layers for recombination” which leads to light emission [124]. The basic OLED that was proposed in 1987 consists of four layers, from top-to-bottom: Cathode, emitting layer, hole-transporting layer, and finally the anode. The emitting layer (EML) consists of a “dopant and host materials with high quantum efficiency and high carrier mobility” [124]. On the other hand, the hole-transporting layer (HTL) brings carriers to the EML for recombination [124]. Modern OLEDs have extra layers, such as the electron-injection layer, electron-transporting layer, and hole-injection layer, which all combine to create the emitting display of an OLED. Additionally, there are two methods to create white light. Those being “RGB OLEDs; and a white OLED with RGB color filters” [124]. We typically see RGB OLEDs for mobile displays, and color-filtered white OLEDs mostly used for large TV displays. Similarly to LCDs, OLED displays have variants that can change their efficiency and use case. The four most common types are: Fluorescence, Triplet-Triplet Fluorescence, Phosphorescence, and Thermally Activated Delayed Fluorescence [124]. A key idea to keep note of, is that for fluorescence-based OLEDs

there are “singlets” that “decay radiatively” [124]. Meaning that the by-product’s percentage of singlets in comparison to other molecule states directly correlates to the efficiency of the display. With that in mind, regular fluorescence OLEDs produce “25% singlets and 75% triplets” in electrical excitement, leading to 25% “internal quantum efficiency (IQE)” [124]. The IQE is basically a measure of what percentage of excited electrons are made into light-emitting electrons. To solve the low efficiency issue, the Triplet-Triplet fluorescent OLED gets two triplets to form a singlet through a triplet fusion process. If we cut the total number of triplets in half and add that to the singlets, we can estimate a theoretical maximum IQE of 62.5% [124]. The last fluorescent display we’ll cover is the Thermally Activated Delayed Fluorescent (TADF) OLED. In this version, “the triplet can jump back to the singlet state by means of thermal energy” giving a theoretical maximum of 100% IQE. The Phosphorescence version of an OLED can also achieve a 100% internal quantum efficiency through “the introduction of heavy metal atoms into the emitters” which “greatly reduces the triplet lifetime” giving more efficient emission. With all of this in mind, the OLED has a few key advantages in comparison to the previously mentioned LCD. Each individual pixel can be turned off or on, leading to better color depth and efficient design when we don’t need every single pixel turned on. If an OLED is to be used for this project, the efficiency of the TADF / phosphorescence OLED would be ideal, specifically TADF due to the exception of heavy metals.

3.1.1.4 Display Comparison Table

	Technology	
	HT1621 LCD	NHD-0.95-9664G OLED
Typical Supply Power	3mW	7mW
Segmented	Yes	No
Cost	\$3 ~ \$10	\$9 ~ \$30
Matrix Mode	Passive	Passive
Display Resolution	6-digit 7-segment	96x64 pixels
Decision: HT1621 LCD	Reasoning:	Lower average power draw and cost

3.1.1.5 RF Transceiver Module Technology Comparison and Selection

To improve the scalability for future iterations of NIMBL, we wanted to consider solutions for how data could be collected and saved. If data could be transmitted and stored externally to the module, customers could develop software to provide various kinds of long-term analysis. While building software of our own to store and further process the data over a longer time scale is outside the scope of our senior design project,

we wanted to preserve the possibility for this feature to exist in the future. Our solution was radio frequency (RF) transmission of pulse and SpO₂ data.

We know that the mode of communication for data storage should be wireless. The reason is simple: the customer should have flexibility in how much data they store. This, combined with the fact that we want the module itself to maintain a relatively low profile, means that we don't want to saddle the user with on-board storage solutions.

Besides being wireless, we also have to ensure that the mode of communication draws relatively low power to preserve a long battery life. And finally, we want our solution to impede the user's ability to use the module as little as possible. With these factors in mind, we have a few options to consider: Bluetooth, WiFi, and RF communication.

The pros of Bluetooth include that it is easy to interface with, having dedicated support on many microcontrollers. Bluetooth also consumes little energy and has many existing APIs to reference for our prototype. One major con of Bluetooth, though, is its short range. Low energy Bluetooth solutions can begin to struggle as early as 35m [78]. Additionally, Bluetooth devices can struggle to overcome interference at the 2.4GHz operating frequency, competing with WiFi and other Bluetooth devices in the same vicinity. When it comes to WiFi, the pros are similar to some of Bluetooth's; pervasive support and strong APIs. Additionally, WiFi is highly capable of transmitting large amounts of data quickly, with rates on the order of Mbps being achievable. However, WiFi also consumes a lot of power to operate continuously, which poses a large issue in maintaining the battery life of our prototype.

Radio Frequency communication has a strong set of pros. We can transmit at low power levels and still maintain excellent range, up to hundreds of meters, worrying less about interference at certain FCC approved frequencies. The cons are as follows: you need to establish a base station (an RF receiver and an interface that handles the transmitted signal), and the data rate is significantly lower than with Bluetooth or WiFi. For the sake of our project, though, we want to focus on developing a versatile foundation to be improved upon later while learning about new topics. We also have to transmit a very low density of data: just two integers a second would be more than enough. Since data rate is not a concern for our project, and we are interested in learning more about RF technologies, we decided to utilize RF for our external data communication.

Based on our research, we will discuss the process of generating, transmitting, and receiving an RF signal at a broad level to inform our technology and component selections. Every RF link involves the same essential chain of operations: creating an electrical signal that represents information, modulating it onto a high frequency carrier, radiating it through an antenna, allowing it to propagate through space, and then capturing and demodulating it at the receiving end. The first step in any RF system is the creation of the signal that carries the intended information. At its most basic level, the signal originates in a low-frequency domain, such as a digital logic line from a microcontroller, an analog audio waveform, or a sensor voltage proportional to some physical measurement. This low frequency signal on its own cannot travel far through free space because their wavelengths are far too long. Long wavelengths require larger

antennas to effectively radiate. For example, a 1 kHz electromagnetic wave has a wavelength of roughly 300 kilometers, an impossible size for any practical antenna. To overcome this, radio systems often utilize a high frequency sinusoidal carrier signal whose wavelength is much smaller (often on the order of centimeters). The low-frequency information is then imposed on, or modulated into, this carrier so that it can be transmitted efficiently.

The carrier itself is generated by an oscillator circuit. In early radio systems, oscillators were built from inductors and capacitors arranged so that the stored energy alternates between magnetic and electric fields at a resonant frequency. Modern transceivers use crystal or surface acoustic wave resonators to stabilize that frequency with extremely high precision. For example, an oscillator circuit might incorporate a quartz crystal that vibrates mechanically at a frequency determined by its geometry and cut angle, producing a stable electrical oscillation when integrated with an amplifier loop. The output of this oscillator provides a pure sinusoidal voltage at a highly stable reference frequency, which can be used as a reference for systems up to GHz frequencies. Once the carrier is generated, the baseband is used to modify one or more properties of that carrier. This process, known as modulation, enables the efficient transmission of information. There are many types of modulation, but they all fall under three basic categories based on which property of the carrier is varied. In amplitude modulation (AM), the instantaneous voltage amplitude of the carrier increases or decreases in proportion to the input signal. In frequency modulation (FM), the carrier frequency shifts slightly above or below its nominal value depending on the baseband waveform. In phase modulation (PM), the carrier's phase angle changes to represent data transitions. Digital systems often use discrete versions of these techniques. Some examples are binary frequency-shift keying (FSK), amplitude-shift keying (ASK), or phase-shift keying (PSK). Before the signal is sent to an antenna, it must be amplified to a sufficient level to ensure adequate radiated power. The device that performs this task is the power amplifier. Amplifier linearity is an important consideration here. Some modulation schemes, such as AM, require that the amplifier preserve the exact waveform shape to avoid distortion, necessitating the use of linear amplifier classes. Others, such as FSK or constant envelope phase modulation, tolerate or even prefer nonlinear amplifier types because they can offer higher efficiency. Many modules include an integrated power amplifier inside of the IC.

After amplification, the RF signal must pass through a filtering and matching stage. Filters remove unwanted harmonics or spurious signals produced by the oscillator and amplifier. Typically, a LPF or BPF is placed between the power amplifier and the matching network port to ensure compliance with spectral masks defined by the FCC. As far as impedance matching is concerned, most RF systems standardize around a characteristic impedance of 50Ω . If the output impedance of the power amplifier does not match the input impedance of the antenna, part of the transmitted power reflects back toward the source, reducing efficiency and potentially causing instability. A matching network composed of inductors and capacitors can be designed to transform the impedances and minimize reflections, ensuring maximum power transfer to the antenna. Once the transmit signal reaches the antenna, it is converted into propagating EM waves. The efficiency of this process depends on the antenna geometry relative to the wavelength of operation. A half-wave dipole, for example, has a length equal to half of

the carrier wavelength, resulting in strong radiation along its perpendicular axis. A quarter-wave monopole uses a conductive ground plane as a mirror image to achieve the same effect. Directional antennas such as patches, Yagi-Uda, or horns focus the energy in particular directions, providing gain that effectively increases the radiated field strength in the desired direction without increasing transmitter power. The relationship between antenna gain, transmitter power, and received power at a distance is described by the Friis transmission equation, which forms the foundation for link budget analysis.

Once the EM wave leaves the antenna, it propagates through air. As it propagates, the field strength decreases with distance due to spreading of the wavefront, which in free space follows an inverse square relationship. The cumulative loss between transmitter and receiver is known as path loss. Because these losses are often large, we must ensure that the transmitted power and antenna gains are sufficient for the receiver to detect the signal with an acceptable margin above its noise floor.

At the receiver, a complementary antenna captures a small portion of the EM energy. This captured energy induces a voltage across the antenna terminals proportional to the electric field strength of the incident wave. Because the received signal power can be extremely low, the first component in the receive chain is almost always a low-noise amplifier (LNA). The purpose of the LNA is to increase the amplitude of the signal while adding as little noise as possible. The LNA's noise figure, which quantifies how much additional noise it introduces, directly affects the receiver's sensitivity. A lower noise figure means the system can detect weaker signals, improving link range. Many RF transceiver modules include an integrated LNA on the IC. After low noise amplification, the signal must be converted back into a form suitable for demodulation by converting to an intermediate frequency (IF)/baseband. Once the signal is at an appropriate frequency, the demodulator extracts the information that was encoded at the transmitter. The exact method depends on the modulation type. In an AM system, an envelope detector or synchronous demodulator recovers the varying amplitude corresponding to the original message. In an FM system, a frequency discriminator or phase-locked loop converts frequency variations into voltage variations. In digital systems using FSK, PSK, or LoRa modulation, the demodulator typically includes a digital signal processor that performs correlation, phase detection, or spectral analysis to determine which symbols were transmitted. The recovered digital bits are then reassembled into packets or data streams for the MCU to interpret.

Throughout both the transmit and receive process, noise is one of the fundamental limitations in RF communications. The minimum detectable signal level of a receiver is determined by its noise floor. The difference between the received signal power and this noise floor defines the signal-to-noise ratio (SNR). Different modulation schemes require different minimum SNRs to achieve acceptable bit error rates. We can decide if our transmitter will be able to communicate (make link) with the receiver by performing a link margin. A link margin describes the amount of excess signal strength available above the minimum required for stable communications. A link margin can be calculated by taking the transmitted power, adding transmitter and receiver antenna gains, subtracting path loss, and comparing the resulting received power to the receiver sensitivity. A positive link margin means the system can tolerate additional losses from obstacles,

misalignment, or fading without failure. If the calculated link margin is too small or even negative, we will have to consider increasing transmit power, using higher gain antennas, reducing the data rate (which lowers the required SNR), or improving receiver sensitivity by using lower noise components. Link margin thus acts as a practical indicator of system reliability in real-world conditions.

For our prototype, the design of a complete RF link requires balancing all these factors. On the transmit side, we must consider modulation bandwidth, power amplifier linearity, spectral efficiency, and thermal management. At the receiver, key parameters include sensitivity, selectivity, and dynamic range. The antennas at both ends must be properly matched and oriented to achieve the desired gain and polarization alignment.

In practice, an RF link also involves other practical constraints. The FCC allocates frequency bands and imposes limits on radiated power and bandwidth to prevent interference. Devices operating in unlicensed bands such as 902–928 MHz must comply with rules like FCC Part 15, which specify maximum output powers and out-of-band emission levels. We must balance necessary FCC compliance with a suitable margin.

3.1.1.5.1 Low-Power Digital Transceiver Modules

Low-power digital transceivers are certainly capable of achieving many of our goals in a suitable fashion. They are typically manufactured to be compliant with FCC regulations, boasting low-power output (0-12dBm) and operation frequencies such as 915MHz (compliant with Part 15.247). Additionally, many are designed to operate at very low sleep currents to preserve power when not actively transmitting or receiving, oftentimes near one microamp of current draw. Additionally, since we only need to transmit a small amount of data per second, we could utilize a lower duty cycle and even further reduce the power drawn. Another strong aspect of low-power digital transceivers is that they can often communicate with the microcontroller via SPI and/or UART interfacing, which are protocols that we are comfortable utilizing. When it comes to the data transmission via RF, if we wish to avoid the implementation of spread spectrum operation with frequency hopping as outlined in Part 15.247, we would have to operate for less than one second per transmission for a total of less than five seconds per minute (instead complying with Part 15.231). However, this should be easily attainable with the incredibly low density of data that we wish to transmit. Additionally, many modules are already configured to perform spread spectrum operation.

3.1.1.5.2 RF Modem Modules (Embedded Radio Modems)

Embedded radio modems are typically FCC compliant out the gate, granted that you do not modify their configuration. The problem with this is that embedded radio modems are a bit overkill for what we are trying to accomplish. First and foremost, they are typically built for the capability of transmitting information on the order of complexity of a waveform as opposed to several integers a second. This is problematic because the module's configuration draws significantly more power than a digital transceiver module designed for low-power operation will. Since we are prioritizing battery life, this is quite restrictive. Additionally, RF modem modules can maintain larger profiles on the order of multiple centimeters, which is not ideal in maintaining the possibility of future downsizing. They also tend to be more expensive than low-power transceiver modules.

All of these factors together make them a great choice for a project who is planning to transmit complex data with a strong out-of-the-box solution, but not ideal for our biomonitoring system.

3.1.1.5.3 Spread-Spectrum / FHSS Telemetry Modules

Frequency-hopping spread spectrum (FHSS) modules are the most robust transmission option available to us. They offer insane range capabilities, with reception being easily achievable up to hundreds of meters from the prototype. The reason that FHSS modules are able to do this at sub-GHz frequencies is because of their increased power output. Without having to follow Part 15.231 and instead being compliant with the frequency hopping protocol outlined in Part 15.247, these modules are granted a higher allowable power ceiling (up to 36dBm EIRP). The disadvantage of this is that FHSS telemetry modules are larger, more costly, and can be significantly more complicated in their implementation for our use case. Ultimately, the most suitable type of module for our project would be a low-power transmitter or transceiver module.

3.1.1.6 RF Transceiver Module Technology Comparison Table

	<u>Technology</u>		
	Low-Power Digital Transceivers	Embedded Radio Modems	FHSS Telemetry Modules
Design Complexity	Lowest	Moderate to High	Moderate to High
Pros	Lower current draw Strong documentation on simple PCB implementations Small profile Inexpensive	High information density FCC compliant out the gate and easily interfaced Long ranged	Robust security options for communication Utilization of FHSS guarantees higher power ceiling Long ranged
Cons	Low information density Lower range	Large current draw Large profile	Large current draw Large profile Costly
Decision:	Low-Power Digital Transceivers	Reasoning:	Inexpensive, with good power efficiency and sufficient range for our application.

3.1.1.7 Antenna Hardware Technology Comparison and Selection

Antennas direct the energy signal transmitted by the module. Differences in antenna shape and material can have implications for the clarity of our transmission. In our project, the antenna should not be highly directive, as we do not want the user to have to point the device towards a base station for their results to be recorded. We also want to ensure that the antenna does not push our EIRP over the FCC guidelines. To meet these goals, we will discuss the different properties of various antenna shapes.

3.1.1.7.1 Dipole

A dipole antenna involves current flowing through two opposite arms. Dipole antennas are utilized to propagate a pattern with high broadside intensity and less radiation at the poles. That is, the gain pattern shows high intensity near the base of both arms and the pattern is symmetrical about their joint.

3.1.1.7.2 Monopole

Compared to the dipole, a monopole antenna has one arm extending up from a ground plane. It can be conceptualized as half of a dipole, so does not necessarily feature symmetry along the length of the antenna. That being said, monopole antennas feature high broadside intensity just like the dipole. This is a compelling aspect of both antenna types, as this low directionality allows a uniform pattern to propagate across the air to a base station at any lateral orientation. Furthermore, energy is concentrated with more intensity in the monopole, as there is less geometry for the wave to spread through before radiating.

3.1.1.7.3 Patch

The patch antenna is rectangular with three layers: a ground plane, dielectric, and conductor stacked on top of one another. This geometry causes the energy to radiate normal to the surface of the patch. While this option is good for achieving a strong gain perpendicular to the patch, this solution is too directional, and would likely fail to link with the base station if the patch were not oriented towards it.

3.1.1.7.4 Yagi-Uda Antenna

The Yagi-Uda antenna is a classic example of a directional array, which achieves high gain through constructive interference of multiple elements. Its architecture typically consists of one driven dipole, a single reflector, and several director elements that focus radiation into a narrow beam, greatly improving forward gain while suppressing unwanted back lobes. At 915MHz, a properly tuned Yagi-Uda antenna can deliver between 9 and 13 dBi of gain, making it an excellent choice for long-range point-to-point communication or controlled coverage testing. That being said, the Yagi-Uda is clearly unsuitable for our project for two major reasons. The antenna is highly directional and its length is often on the order of multiple wavelengths, which makes it unsuitable for our system that should be relatively compact and remain agnostic to the location of the base station relative to the prototype.

3.1.1.7.5 Horn Antenna

Horn antennas operate by flaring a waveguide section to gradually transition from a confined mode to free-space propagation. When scaled for 915 MHz operation, a horn can achieve 10–15 dBi of gain with very low sidelobe levels, making it suitable for similar application cases to the Yagi-Uda. The smooth, continuous structure allows for high power handling and stable phase response, features that make horn antennas common as calibration standards and measurement references. The major problems with the horn antenna are its dimensions and fabrication constraints. In addition to these issues, it is also highly directional, once again making it unsuitable for our application.

The first three antenna shapes are most interesting and will be the subject of the following technology table. The Yagi-Uda array and the horn antenna are both very thoughtful designs, but they are not applicable for the small form factor and omnidirectional preference of our prototype.

3.1.1.8 Antenna Hardware Technology Comparison Table

	Technology		
	Dipole	Monopole	Patch
Design Complexity	Low	Low	Moderate
Pros	Uniform azimuthal propagations	Moderate size Uniform azimuthal propagations High intensity	Small size
Cons	Large size	N/A	Highly directional
Decision:	Monopole	Reasoning:	Inexpensive, strong omnidirectional gain pattern, relatively small dimensions.

3.1.1.9 Case Material Technology Comparison and Selection

NIMBL will need cases to house the electronics so that the device can be used effectively as intended. All group members have access to 3D printers, making it an easy choice for the means of constructing the cases. Unlike using plywood, sheet metal, or other case constructions, 3D printing with plastic allows for quick prototyping and design of geometries ranging from simple to complex. Basically, almost any part can be quickly made using only one tool, the printer. However, there are many different types of plastics

to print with, each requiring different print settings, hardware, and expertise. So, three of the simplest to print filaments were chosen for the comparison: PLA, PETG, and PCTG.

3.1.1.9.1 PLA

PLA stands for polylactic acid and it is an extremely common plastic 3D printer filament. Specifically, it is a thermoplastic polymer, and plant products like cornstarch or sugar cane are used to make the lactic acid. Other additives can be mixed in to change the material properties; PLA filaments with heavy mixtures are often denoted as PLA+. PLA bonds very well with plastic that has been recently cooled and has a high tolerance to different extruding temperatures and printer settings. This makes it very easy to print, especially for beginners. However, PLA is a poor choice for functioning parts. It has a high tensile strength and stiffness, but this is misleading since PLA has poor fracture resilience. This means if the PPG device is dropped with a PLA case, it will shatter. Also, this plastic is vulnerable to water, chemicals, abrasion, and cannot survive outdoors, especially in sunlight. PLA does not require a heated bed or enclosure. Though, it is recommended to have a heated bed set to 45°-70° C. Some other requirements are a nozzle temperature between 190°-220° C; print speed of 30-90 mm/second; an extruder fan set to maximum speed; a retraction speed of 30-80 mm/second; a retraction distance of 2-5 mm for Bowden drives or 1-2 mm for direct drives; a layer height of 0.2 mm for conventional speed and quality; and a glass, aluminum, painter's tape, PEI, or glue stick build surface. No special hot-end is required either [72], [73].

3.1.1.9.2 PETG

PETG is polyethylene terephthalate (PET) plastic modified by replacing some of the ethylene glycol with cyclohexanedimethanol to make the plastic less brittle, clearer, and easier to print. PETG has great thermal characteristics; it can cool efficiently and is not prone to warping. Unlike PLA, PETG also has high chemical and impact resistance. It is also more resistant to ultraviolet radiation. PETG is very good for making waterproof parts like bottles. This is despite the fact that PETG is also highly hygroscopic, meaning it absorbs moisture from the air, which can cause defects in prints. This makes PETG harder to store than PLA. After printing, however, PETG's hygroscopic properties do not affect the quality and properties of the finished part. Another disadvantage of PETG is that its surface finish is very soft, meaning parts will be susceptible to abrasion. Just like PLA, PETG is also known for its ease of printability. It is recommended to use an extruder temperature of 220°-260° C; a heated bed should be used with a temperature of 70°-90° C; 40-60 mm/second print speed; 35-40 mm/second retraction speed; for Bowden drives 5-7 mm retraction distance, and 2-4 mm for direct drives; a layer height of 0.28 mm; and a textured PEI, glue stick, or painter's tape build surface. A cooling fan is required, but no special hot-end is. Though, it is recommended to use an all-metal hot-end [74], [PETG2], [PETG3].

3.1.1.9.3 PCTG

Taking PET and replacing all the ethylene glycol with cyclohexanedimethanol produces PCT [PLAWiki]. PCTG is PCT with added glycol, making it easier and suitable for 3D printing [PCTGWiki]. PCTG is an upgrade compared to PETG. PCTG carries many of the same properties as PETG, but is stronger, has more impact resistance, greater

chemical resistance, and much better ultraviolet radiation resistance. This makes PCTG a more suitable option for medical devices, electronic housings, engineering-grade parts, and other end-use parts. PCTG is also relatively easy to print. Generally, PCTG requires a heated bed at 80° C, an extruder temperature between 250° and 270° C, a print speed of 40-60 mm/second, and every other requirement is the same or very similar to PETG. Finally, an all-metal hot-end is required. This filament is recommended for experienced printers as the temperature requirements push the boundaries of many beginner-level printers [PETG3], [75], [76], [77].

3.1.1.9.4 Case Material Technology Selection and Reasoning

Overall PCTG is the best choice for the case material. Although it is recommended for experienced printers, its advantages over the other filaments make it the clear choice. Since the PPG will be a hand-held device, it needs to be able to survive constant handling as well as drops. Also, the PPG is intended to be an end-use product, not just a prototype, so using the more robust PCTG is the best option. Also, PCTG's waterproof and chemical resistant properties are essential as this device may be used in a clinical environment where it will have frequent exposure to cleaning, sterilizing, and disinfecting agents.

3.1.1.10 Case Material Technology Comparison Table

	Technology		
	PLA	PETG	PCTG
Printability	Easiest	Easy	Less easy
Impact Resistance	Poor	Good	Very good
Chemical Resistance	Poor	Good	Very good
Abrasion Resistance	Lowest of the three	Between the other two	Highest of the three
Ultraviolet Resistance	Poor	Okay	Very good
Heated Bed Required	No	Yes	Yes
Heated Bed Temp.	45°-70° C	70°-90° C	80° C or greater
Enclosure Required	No	No	No
Extruder Temperature	190°-220° C	220°-260° C	250°-270° C
Hot-End	No special requirements	All-metal recommended	All-metal required
Print Speed	30-90 mm/second	40-60 mm/second	40-60 mm/second
Extruder Fan	Yes	Yes	Yes
Retraction Speed	30-80 mm/second	35-40 mm/second	35-40 mm/second
Retraction Distance	Bowden Drive: 2-5 mm	Bowden Drive: 5-7 mm	Bowden Drive: 5-7 mm

	Direct Drive: 1-2 mm	Direct Drive: 2-4 mm	Direct Drive: 2-4 mm
Layer Height	0.2 mm	0.28 mm	0.28 mm
Build Surface	Glass, aluminum, painter's tape, PEI, or glue stick	Textured PEI, glue stick, or painter's tape	Textured PEI, glue stick, or painter's tape
Decision:	PCTG	Reasoning:	Robustness and survivability

3.1.2 Part/Product Comparison and Selection (Hardware)

3.1.2.1 PPG Sensor Part Comparison and Selection

Unfortunately, there are not very many options for PPG sensors that fit our project scope in terms of complexity and function. We require a sensor module with full integration to avoid design constraints associated with making low-noise hardware, and the sensor must be able to be hand-solderable to a board. A lot of sensors available on the market do not have full integration and are only offered in packages that we are unable to utilize. Also, some of the sensor options with full integration are obsolete or becoming obsolete (as of Oct. 2025). Luckily, three sensors are available with full integration and at least Infrared, Red, and Green wavelength LEDs. These options are the MAX30101, the MAXM86161, and the MAX86916.

3.1.2.1.1 MAX30101 PPG Sensor Module

The MAX30101 is a reflective mode PPG sensor that integrates infrared, red, and green LEDs and the photodetector into an IC chip. It also includes drivers to modulate the LEDs for SpO₂ and pulse measurements. The currents for each LED can be programmed from 0 to 50mA, and the pulse width can be programmed from 69 μ s to 411 μ s to optimize measurement accuracy and power consumption of the device. Additionally, a temperature sensor is included on-chip. This sensor allows for calibration of the sensor's data to improve the accuracy of SpO₂ when ambient temperature changes cause errors. The temperature sensor has a resolution of 0.0625°C [58].

The sensor also fully integrates ambient light cancellation. The ambient light cancellation uses a Track/Hold circuit to cancel up to 200 μ A of current. This increases the effective dynamic range of the sensor. A proprietary discrete time filter is used to reject frequency interference from changing ambient light as well. The MAX30101 utilizes a continuous time oversampling sigma-delta converter ADC that has 18 bits of resolution. The output data rate of the ADC is programmable from 50 samples per second (sps) to 3200 sps. The full-scale ranges of the ADC can also be programmed from 2 μ A to 16 μ A. The sensor stores sample data in a FIFO that can store 32 samples of data (32 words deep). Each sample word utilizes three bytes per sample channel and can be configured to be up to 12 bytes in size. The FIFO allows samples to be temporarily stored so that the microcontroller reading the data does not have to be perfectly synchronized with the sensor's output. This avoids data being lost or overwritten [58].

This PPG sensor has an operating temperature range of -40° C to 85° C. It requires two power supplies: 1.8 V for the sensor itself and 5.0 V for the LEDs. The device can be shutdown through software with a standby current of 0.7 μ A typical. It communicates to the microcontroller via I²C. The sensor has an Organic Land Grid Array (OLGA) package, which is very similar to a DFN Package. There are two rows of seven pins on each side of the sensor for a total of 14. The package dimensions are 5.6 mm x 3.3 mm x 1.55 mm. Glass is integrated with the package to protect the LEDs and photodetector. It is recommended that the sensor is used for wearable devices, smartphones, and tablets [58].

3.1.2.1.2 MAXM86161 PPG Sensor Module

The MAXM86161 is a reflective mode PPG sensor that has a very similar design as the MAX30101. It too integrates infrared, red, and green LEDs and the photodetector into an IC chip. The MAXM86161 includes three eight-bit DAC drivers to modulate the LEDs for various optical measurements. The full scale currents for each LED driver can be programmed to 31, 62, 94, and 124 mA, and the pulse width can be programmed from 4.8 μ s to 117.3 μ s to optimize Heart Rate, Heart Rate Variability, and SpO₂ measurement accuracy and power consumption of the device. A PIN photodiode is used as the detector [59].

The sensor also fully integrates ambient light cancellation. The ambient light cancellation uses a proprietary scheme to cancel up to 200 μ A of ambient light current. A proprietary discrete time filter is used to reject 50/60 Hz interference and changing ambient light from the measurements with greater than 70 dB of ambient rejection at 120 Hz. The MAXM86161 utilizes a continuous time oversampling sigma-delta converter ADC that has 19 bits of resolution. The output data rate of the ADC is programmable from 8 samples per second (sps) to 4096 sps. The full-scale ranges of the ADC can also be programmed from 4 μ A to 32 μ A. Also, a dynamic power down mode is supported for sample rates 256 sps and lower to reduce power consumption between samples. The sensor stores sample data in a FIFO that can store 128 samples of data (128 words deep). Each sample word is 3 bytes wide including a 5-bit tag width. Also, a proximity mode is included, which drops the LED current, reduces the sample rate to 8 sps, and puts the sensor into low power mode when the device is not in-contact with the skin to reduce energy usage. Finally, a Picket Fence Detect-and-Replace Function is built-in to correct ambient light correction errors when the device is in conditions when the ambient light changes rapidly [59].

This PPG sensor has an operating temperature range of -40° C to 85° C. It requires a single power supply of 3.0 to 5.5 V. The device can be shutdown through software with a standby current of 1.6 μ A typical. It communicates to the microcontroller via I²C. The sensor has an Organic Land Grid Array (OLGA) package. There are two rows of seven pins on each side of the sensor for a total of 14. The package dimensions are 2.9 mm x 4.3 mm x 1.4 mm. Glass is integrated with the package to protect the LEDs and photodetector. It is recommended that the sensor is used for mobile and in-ear applications [59].

3.1.2.1.3 MAX86916 PPG Sensor Module

The MAX86916 is a reflective mode PPG sensor that integrates infrared, red, green, and blue LEDs and the photodetector into an IC chip. It also includes drivers to modulate the LEDs for SpO₂ and pulse measurements. The currents for each LED can be programmed from 0 to 150mA, and the pulse width can be programmed from 70 μ s to 420 μ s to optimize measurement accuracy and power consumption of the device. Additionally, a DAC is used to subtract a DC component of the received signal at the photodetector that is united with the pulse of the LED to reduce cross-talk in the optical measurements [60].

The sensor also fully integrates ambient light cancellation. The ambient light cancellation uses a Track/Hold circuit to cancel up to 200 μ A of current. A proprietary discrete time filter is used to reject 100/120 Hz interference from artificial lights and interference from changing ambient light as well. The MAX86916 utilizes a continuous time oversampling sigma-delta converter ADC that has 19 bits of resolution. The output data rate of the ADC is programmable from 50 samples per second (sps) to 3200 sps. The full-scale ranges of the ADC can also be programmed from 4 μ A to 32 μ A. The sensor stores sample data in a FIFO that can store 32 samples of data (32 words deep). Each sample word utilizes three bytes per data item and can be made of up to four data items. Also, a proximity mode is included to save power by reducing visible light emission when tissue is not in front of the sensor [60].

This PPG sensor has an operating temperature range of -40° C to 85° C. It requires two power supplies: 1.8 V for the sensor itself and 5.0 V for the LEDs. The device can be shutdown through software with a standby current of 0.7 μ A typical. It communicates to the microcontroller via I²C. The sensor has an Organic Land Grid Array (OLGA) package. There are two rows of seven pins on each side of the sensor for a total of 14. The package dimensions are 3.5 mm x 7.0 mm x 1.5 mm. Glass is integrated with the package to protect the LEDs and photodetector. It is recommended that the sensor is used for wearable devices, smartphones/accessories, tablets, and fitness assistant devices [60].

3.1.2.1.4 Reflective PPG Sensor Part Selection and Reasoning

The MAX30101 was chosen to be the sensor utilized for the project. The reason is all three sensors have minimal differences in performance, so the biggest factor becomes cost and usability. The MAXM86161 only has development boards that are around \$200. This makes developing a prototype for this sensor incredibly unaffordable, and therefore, the project would not be able to progress past the early development stage if this sensor was used. Of the two remaining sensors, the MAX30101 has the cheapest development boards and sensor ICs. Also, even though the MAX86916 has an additional blue wavelength for advanced capabilities, the blue LED would be useless to the device since the project scope is to just measure SpO₂ and Pulse Rate. Finally, the MAX30101 is an older sensor, so it has more information available on the internet to assist with designing and trouble-shooting than the MAX86916.

3.1.2.2 PPG Sensor Part Comparison Table

	<u>Part</u>
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	MAX30101	MAXM86161	MAX86916
Integrated LEDs	Wavelengths: Infrared, Red, and Green Current: Programmable, 0 - 50 mA Pulse Width: Programmable, 69 - 411 μ s	Wavelengths: Infrared, Red, and Green Current: Programmable; 31, 62, 94, and 124 mA Pulse Width: Programmable 14.8 - 117.3 μ s	Wavelengths: Infrared, Red, Green, and Blue Current: Programmable, 0 - 150 mA Pulse Width: Programmable, 70 - 420 μ s
Ambient Light Cancellation	Up to 200 μ A	Up to 200 μ A	Up to 200 μ A
Discrete Time Filter	Unlisted frequency rejection	Rejects 50/60 Hz	Rejects 100/120 Hz
ADC	Type: continuous time sigma-delta Resolution: 18 bit Output data rate: programmable, 50 - 3200 samples per second (sps) Full-scale ranges: programmable, 2 - 16 μ A	Type: continuous time sigma-delta Resolution: 19 bit Output data rate: programmable, 8 - 4096 samples per second (sps) Full-scale ranges: programmable, 4 - 32 μ A	Type: continuous time sigma-delta Resolution: 19 bit Output data rate: programmable, 50 - 3200 samples per second (sps) Full-scale ranges: programmable, 4 - 32 μ A
FIFO	Depth: 32 sample words Data per sample: 12 bytes	Depth: 128 sample words Data per sample: 3 bytes	Depth: 32 sample words Data per sample: 12 bytes
Operating Voltage	1.8 V for the IC and 5.0 V for the LEDs	Single supply; 3 to 5.5 V	1.8 V for the IC and 5.0 V for the LEDs
Operating Temperature	-40° C to 85° C	-40° C to 85° C	-40° C to 85° C
Shutdown Standby Current (typ)	0.7 μ A	1.6 μ A	0.7 μ A
Communication	I ² C	I ² C	I ² C
Package	Type: OLGA Pin Count: 14 pins (two rows of 7) Dimensions: 5.6 x 3.3 x 1.55 mm	Type: OLGA Pin Count: 14 pins (two rows of 7) Dimensions: 2.9 x 4.3 x 1.4 mm	Type: OLGA Pin Count: 14 pins (two rows of 7) Dimensions: 3.5 x 7.0 x 1.5 mm
Vendors for Sensor IC	Analog Devices Digikey Mouser Electronics Newark	Analog Devices Mouser JAK Electronics	Analog Devices Digikey
Vendors for Dev Boards	Plenty	Analog Devices Mouser DigiKey	Analog Devices Mouser Digikey

		Newark	
Cost for IC (from Analog Devices)	\$59.50 for five sensors	\$47.20 for five sensors	\$65.68 for five sensors
Average Cost for Dev Board	~\$30	~\$184	~\$48 to \$210
Additional Features	Temperature Sensor	Picket Fence Detect and Replace Algorithm Detects HRV Dynamic power down mode Proximity mode	Proximity Mode Cross Talk Cancellation DAC
Decision:	MAX30101	Reasoning:	Cost and Usability

3.1.2.3 RF Module Part Comparison and Selection

For this project, significant PCB design is expected. We must select an RF module that will effectively communicate at an allowable frequency and power level. It would be ideal if existing works point in a direction for how to implement data communication using whichever part is selected.

3.1.2.3.1 *Ti CC1101*

This transceiver module is extensively documented by Texas Instruments. In addition to this, they offer a tool that allows the user to easily initialize many aspects of the module's communication protocol. It is capable of communicating at the previously discussed 915MHz frequency with an output power level of ~11dBm according to the datasheet. This is well under the 36dBm requirement if FHSS is utilized, giving us room to choose a desirable antenna to further improve the module's ability to communicate while staying well within FCC regulations. Furthermore, Ti has extensive documentation on how to integrate this chip into a communication system and ensure that it is compliant with FCC regulations. Another strong aspect of the Ti CC1101 is that it has 0.5mm pin spacing, making it solderable in the conditions of our laboratory. These modules are available to ship immediately from Mouser and DigiKey in cut-tape format.

3.1.2.3.2 *HopeRF RFM69CW*

The HopeRF module is similarly well-documented to the Ti CC1101 and maintains all of the same relevant capabilities. It also enables a higher configurable output power (13dBm). However, it is slightly more difficult to procure easily implementable circuit diagrams that enable this module to be utilized for our project. That is, it is harder to locate chip versions of this module that have strongly documented accompanying circuitry to meet the significant PCB design requirement. One major drawback of this module is that it isn't available to ship on either Mouser or DigiKey, nor have we been able to find any readily available option to obtain the IC of this module in a timely manner.

3.1.2.3.3 Linx HUM-900-PRO

The HUM-900-PRO offers a fully self-contained, frequency-hopping UART module that minimizes firmware and RF design effort, making it ideal for quick prototyping or certified product development. This module also suffers from the same problem as the HopeRF RFM69CW module; that is, the proprietary Linx transceiver IC is not readily available for purchase. This means that it would be much more difficult to contribute significant RF PCB design utilizing this component.

3.1.2.3.4 Semtech SX1276

The Semtech SX1276 is a high-performance transceiver that supports both traditional FSK and LoRa modulation schemes, making it flexible for low-power, long-range communications. Like the CC1101, it is capable of operation in the ISM band, with an output power configurable up to approximately 20dBm when using the integrated power amplifier. This provides ample headroom to optimize link performance while maintaining compliance with FCC Part 15.247 requirements. Semtech provides documentation, reference designs and software libraries, which would be useful in integrating with the PCB. The primary disadvantage of the SX1276 is that it requires a more complex initialization sequence and more power management oversight than simpler modules such as the CC1101. It is available via both Digikey and Mouser.

3.1.2.3.5 Nordic nRF905

The Nordic nRF905 is a single-chip transceiver designed for sub-GHz communication in the 433, 868, and 915 MHz ISM bands. It features a fully integrated frequency synthesizer and low-current operation, making it power efficient. The maximum output power is 10dBm, placing it well below FCC emission thresholds and thus suitable for continuous operation in unrestricted environments. Nordic Semiconductor provides a highly detailed product specification, reference layout, and register configuration guide, which would be helpful in integrating the chip into our system. One large drawback is that its modulation flexibility is limited. This module only supports GFSK and it lacks adaptive spreading and coding capabilities. It is available via both Digikey and Mouser.

3.1.2.3.6 Microchip MRF89XA

The Microchip MRF89XA is a compact sub-GHz transceiver designed to operate in the ISM bands. It supports both FSK and OOK modulation with programmable data rate. The module can deliver a maximum output power of about 13dBm, which keeps it within FCC Part 15.247 limits for non-hopping systems. Microchip offers application notes, firmware libraries, and evaluation boards, providing a clear path to system integration. The main advantage of the MRF89XA is its simple SPI interface and well-documented command structure, making it easy to control from microcontrollers such as the MSP430 or PIC families. However, the module is not as widely adopted as the CC1101 or SX1276, so there are fewer open-source design references. In addition, its available development hardware is limited compared to other options discussed. The largest drawback is that this chip is no longer manufactured, making it very difficult to obtain and effectively obsolete.

3.1.2.3.7 Silicon Labs Si4463

The Si4463 transceiver module is a highly configurable sub-GHz wireless IC that supports operation across a wide frequency range from 119MHz to 1GHz. It offers flexibility in modulation schemes and can achieve data rates up to 1 Mbps. The chip's integrated synthesizer and automatic packet handling features are strong showings for a transceiver meant for data communication. Silicon Labs provides a configuration tool called WDS (Wireless Development Suite) that simplifies register setup, and their documentation includes several application notes covering PCB layout, matching network design, and antenna integration. The Si4463 does have some major drawbacks in the context of our prototype, which requires dependable transmission at low data rates. The first of these limitations lies in the configuration complexity. The Si4463's flexibility comes at the cost of a complicated register map that requires multiple initialization sequences to set up modulation, frequency deviation, and packet framing. The WDS software can generate initialization code, but the resulting firmware can be difficult to interpret. Furthermore, while this module has significant documentation from its manufacturer, it does not have as much public interest or user documentation as alternatives like the CC1101 or RFM95, which complicates the prototyping process. It is readily available from both Digikey and Mouser.

The first three modules are most interesting and will be the subject of the following part comparison table. While it was worthwhile to explore the SX1276, nRF905 and MRF89XA, these modules fall noticeable short when it comes to the extent of their documentation, development board options, and/or availability.

3.1.2.4 RF Transceiver Module Part Comparison Table

	<u>Component</u>		
	Ti CC1101	HopeRF RFM69CW	Linx HUM-900-Pro
Pros	Low current draw Strong documentation Software configurator	High data rate possible	High data rate possible UART Communication
Cons	Lower possible output power SPI Only	Moderate current draw SPI Only IC not available from major retailers	Moderate current draw IC not available from major retailers
Decision:	Ti CC1101	Reasoning:	Low current draw, best documentation,

			and reasonably attainable.
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Ultimately, the most suitable component for our project would be the Ti CC1101. It is extensively documented, capable of achieving the communication we desire at a low operating amperage, and demonstrates reliable methods of attainment for the timescale of NIMBL's development.

3.1.2.5 Monopole Antenna Part Comparison and Selection

3.1.2.5.1 *Quectel YECT003AA*

This monopole whip has an SMA M port, which is compatible with the existing reference design from Ti for integrating the Ti CC1101. The antenna's length is parallel to the SMA port. This antenna is not designed specifically as a quarter-wavelength monopole centered at 915MHz.. Its dimensions (113mm length) provide a stronger gain outside of the ISM band that we plan to utilize, with its strongest gain measured in the vicinity of 2.4GHz instead [81]. That being said, it still demonstrates acceptable performance compared to an isotropic radiator in the ISM band ($\sim -0.9\text{dBi}$). This antenna is in-stock via Digikey, but not Mouser. It retails for approximately \$2.92, making it a very inexpensive option.

3.1.2.5.2 *Nearson S161AH-915R*

This antenna is similar to the Quectel YECT003AA in that it utilizes an SMA M termination. This antenna is also more specifically designed for performance in the ISM band, with relatively strong peak E-Plane Gain ($\sim 0\text{dBi}$) at 900 and 928MHz [82]. However, the antenna's length runs perpendicular to the SMA port, meaning that the peak gain would be concentrated normal to the plane of the PCB. This is not ideal, as the base station will likely be on relatively level elevation with the user. We would prefer to maximize the gain in the direction that runs parallel to the PCB. This antenna is in-stock via Digikey, but not Mouser. It retails for approximately \$19.20, making it a fairly expensive option.

3.1.2.5.3 *Abracon AEACAC054010-S915*

Like the previous two antennas discussed, the Abracon AEACAC054010-S915 terminates in an SMA M port. This antenna boasts very similar performance to the Nearson S161AH-915R in the E-Plane [83]. However, this antenna is oriented with its length running parallel to the SMA termination. This means that we can easily capitalize on the maximized radiation of the antenna. This antenna is in-stock via Mouser, but not DigiKey. It retails for approximately \$6.83, making it a moderately priced option.

3.1.2.6 Monopole Antenna Part Comparison Table

	<u>Component</u>		
	Quectel YECT003AA	Nearson S161AH-915R	Abracon AEACAC054010-S915
Pros	Acceptable gain in ISM band Inexpensive	Good gain in ISM band	Good gain in ISM band
Cons	Designed broadly for WiFi as well as ISM Long dimensions	Expensive Runs perpendicular to board	Moderately expensive
Decision:	Quectel YECT003AA	Reasoning:	Inexpensive, acceptable gain in ISM band.

3.1.2.7 MCU Part Comparison and Selection

Arguably one of the most important parts to choose for the project is the MCU, or Micro-Controller Unit for short. This piece is what does all of the mathematical processing, data reading, and results displaying. For the micro-controller to be effective, it must fit well with the other parts the project plans on incorporating. In our project that means the processor must have several communication protocols to ensure we can send out RF signals and read the data coming from our PPG sensor. Furthermore, there should be sufficient on-board storage to allow significant data processing with complex math. This section will review several types of MCUs that have been chosen for similar projects, why they were chosen, and what we can gain from their findings.

One such paper that yielded great information was “IoT-Based Heart Rate Monitoring: A Comparative Analysis of Microcontroller Systems for Real-Time Health Monitoring” [125]. In this article, the authors went into detail about three styles of MCUs, with their advantages, disadvantages, and what made them stand out. One such style was a low-end processor such as the PIC16F84. The goal of this was to do some basic math with the raw sensor data to display the heart rate onto an LCD. It worked by using a PPG sensor to send IR LED lights into the skin, and a phototransistor would read the variations in light absorption which generated an analog signal [125]. Crucial additions to this model were op-amps to amplify the analog signal provided, and a low-pass filter to terminate any high-frequency noise. These two highlights are important to note, as these would allow our project to get more accurate readings. This method was stated to be great for home monitoring, but not something that is practical for “remote monitoring in real-time” [125]. This refers to wifi-communication that is detailed for later revisions. While it is a

good idea to take note of, our scope currently doesn't include wifi communication. Thus, this low-end style of MCU would fit the project great.

The next logical step is to get a slightly more powerful MCU to add more features that could be of use. This is where a processor such as the ATMEGA32 comes into play. Wireless communication was one of the most highlighted additions of this board. Specifically, the ability to use SMS, short messaging system, to send text messages of vitals. However, this introduces a security risk. If a user's vitals are being sent out, it allows a bad actor to see the data and possibly tamper with it to show inaccurate data. While it isn't a guarantee this can and would happen, it is something to take note of. Unfortunately, SMS currently doesn't fit within the project. This section did provide an advantage of this processor that would be great for the product. The addition of an ADC gives us more detailed data processing through the Discrete Fourier Transform. With a mathematical method to compute an analog signal into data given to us, we know what to aim for. A processor that includes ADC is a must. One such class of processor is the MSP430, which has been specifically highlighted in this paper to have "improved power efficiency and more precise signal" than the ATMEGA32. Since the MSP430 class of processor is an area we all have experience in, it seems like a great fit for the project scope.

For a wider project scope, looking towards the ESP8266 would be a great starting point. In [125], the authors highlight its strength in internet connection, which allows for cloud platform communication, and for IoT, internet of things, to integrate more. One way this could expand the project is through cloud data logging, where trends of heart rates could be seen. While this does increase the complexity and allow for more advanced online tools, that isn't inside of our project scope so far. A chip such as the ESP8266 does highlight the importance of additional features. These features will vary from project-to-project, we must now look into what our particular project needs to pick a micro controller which best fits our goals. From the previous section, we know that ADC is a must-have to get an accurate reading of heart-rate and blood oxygen levels. Since there are external parts that will transmit data, the processor must support several communication protocols such as SPI, UART, and I2C. A series of chips that meet this data communication are the MSP430 and ATMEGA32 mentioned previously [126].

Since we have seen what other projects have looked at to pick the best-fitting MCU, we can identify the features our project requires. First, using op-amps to amplify any signal in combination with a low-pass filter to reject high frequency noise. While not directly a part of the MCU, it would greatly assist in clear data reading. Second, Fourier transforms to accurately read analog signals. Since accurate readings are a main goal, this addition is something that is needed, which means our processor should be able to handle complex math and have sufficient on-board storage with enough bits to store a wide range of numbers. Additionally, a board with low-power modes to increase battery life is a must-have. The paper [126] specifically highlighted the importance of power efficiency with battery-powered systems, with the following processor families mentioned: MSP430, STM32, and Kinetis being some examples. Another requirement for smooth development is a strong software development environment. Having a solid set of

software tools allows us to speed up prototyping and catch errors easily [126]. This team all has experience with TI's MSP430 development environment, but other processors such as STM32, ATMEGA32, and ESP32 all also contain ways to easily build software.

With research in other similar projects and analyzing our requirements, the team has narrowed-down the list of MCUs that best-fit the project scope. One is a chip we have experience with is the MSP430FR6989. This processor has everything that we need to accomplish the project. It has a developer board, ADC, communication protocols, timers, low-power mode, and a wide range of operating temperatures. It is a solid chip to select, since it meets all the requirements and lets us work with previous experience. Another chip from TI that we can see using is the MSP430FR2475. It has all the same features as the MSP430FR6989 while costing less. The trade-offs though are smaller nonvolatile memory and less GPIOs. However, this would be a better choice overall as the downsides don't affect us too much. Another selection is the ATMEGA32. It has sufficient RAM, ADC, and communication protocols. Unfortunately a key feature it is missing is the low-power mode. It would still be a usable MCU, but the battery life would suffer from the exclusion of drawing less power.

3.1.2.8 MCU Part Comparison Table

	Technology		
	MSP430FR2475	ATMEGA32	ESP8266
Operating Voltage	1.8v ~ 3.6v	2.7v ~ 5.5v	2.5v ~ 3.6v
Analog-Digital Converter	12-bit	10-bit	10-bit
Digital-Analog Converter	6-bit	N/A	N/A
Max Clock Speed	16MHz	16MHz	160MHz
Low Power Mode	Yes	Yes	Yes
Decision:	MSP430FR2475	Reasoning:	Dedicated DAC and lowest operational voltage

3.1.2.9 Wire Harness Connector Part Comparison and Selection

This project will use multiple PCBs to make the device easier to build and repair if a component fails. This means reliable PCB-to-PCB connections are needed. Using wires to connect the PCBs is the best option since they provide the greatest flexibility in the positioning of the boards. Directly soldering the wires is a viable option, however, the permanent nature of this type of connection can hinder repairs if a PCB board needs to be swapped. So using plug-and-socket connectors for the wires would be extremely

beneficial for the project. Specifically, positive latching rather than friction fitting plug-and-socket connectors should be used as the latch provides a guarantee that the boards will stay connected even when the PPG device is moved and dropped.

3.1.2.9.1 Molex Micro-Lock Plus

The Molex Micro-Lock Plus (MMLP) is a positive latching connector with a wide latch positioned on the top of the connector (the widest portion of the connector). The latch produces an audible click so that it is easy to tell the connectors are successfully mated. MMLPs are offered in single and dual row configurations. The dual row configuration can be purchased with 1.25 mm pitch and can have eight to 42 pins. Dual row versions have an inner latch. Single row connectors are offered in 1.25 mm, 1.50 mm, or 2.00 mm pitches and with two to 16 pins. Also, PCB headers are offered in vertical and right angle forms. A four pin, 1.25 mm pitch right angle MMLP PCB header is 8.25 mm wide and 3.9 mm tall. It has a maximum current rating of 1.5 A per contact and can handle 50 V DC/AC (RMS). It can operate in temperatures of -40° C to 105° C. Additionally, MMLPs can be purchased with potting capabilities, but this may be overkill for this project's scope [67], [68].

3.1.2.9.2 Molex Pico-Lock

The Molex Pico-Lock (MPL) is also a positive latching connector, but it differs from the MMLP in that the MPL has two latches, each on the small sides of the connector. Also, there are additional friction locks to help ensure mating quality. MPLs are only offered in single row configurations, but they have a wide range of pitch options. Specifically, they can be purchased in 1.00 mm, 1.50 mm, 2.00 mm, and 3.00 mm pitch configurations. Each pitch can have two to 12 pins. Only right angle PCB headers are available for MPLs. A 1.50 mm pitch, four pin PCB header is 9.75 mm wide and approximately 2 mm tall. It can handle a maximum of 3.0 A per contact and a maximum of 150 V DC/AC (rms). Its operating temperature ranges from -40° C to 105° C [69], [70].

3.1.2.9.3 JST GH

The JST GH connector is positive latching with a wide latch on top of the widest face of the connector. It is only offered with a 1.25 mm pitch, but it does have right angle and vertical PCB headers. Also, it is only offered in a single row configuration. The connectors can be purchased with two to 15 pins. A four pin right angle header is 8.25 mm wide and is 4.25 mm tall. They are rated for 1 A and 50 V AC/DC, and can operate at temperatures ranging from -25° C to 85° C [71].

3.1.2.9.4 Wire Harness Connector Part Selection and Reasoning

Since all of the researched connector options are roughly the same size and can handle voltages and currents well within our estimated operating ranges, choice really comes down to availability and pin count, with availability being the most important. The two Molex connectors are only available from distributors like Digikey and Mouser. However, since hobbyists typically use JST branded connectors, Amazon offers a good number of pre-crimped wire and connector kits for the GH connector. Pulse the wide number of pin options for the GH provides plenty of versatility for using this connector for different subsystems of this project.

3.1.2.10 Wire Harness Connector Part Comparison Table

	<u>Part</u>		
	Molex Micro-Lock Plus	Molex Pico Lock	JST GH
Latch Type	Wide	Side	Wide
Row Configurations	Single Dual	Single	Single
Pitch	Single: 1.25, 1.5, and 2 mm Dual: 1.25 mm	1, 1.5, 2, and 3 mm	1.25 mm
Pin Count	Single: 2 to 16 Dual: 8 to 42	2 to 12	2 to 15
Header Angles	Right and Vertical	Right	Right and Vertical
Current Rating	1.25 mm pitch: 1.5 A	1.5 mm pitch: 3.0 A	1 A
Voltage Rating	1.25 mm pitch: 50 V DC/AC (RMS)	1.5 mm pitch: 150 V DC/AC (rms)	50 V DC/AC
4 Pin Configuration Right Angle Header Dimensions	Width: 8.25 mm Height: 3.9 mm	Width: 9.75 mm Height: 2 mm	Width: 8.25 mm Height: 4.25 mm
Operating Temperature	-40° to 105° C	-40° to 105° C	-25° to 85° C
Decision:	JST GH	Reasoning:	Availability

3.1.3 Power System

3.1.3.1 Overall System Requirements

<u>Power Distribution</u>		
Component	Input Voltage	Input Current
MAX30101 PPG Sensor	3.3V	51.1mA (max)
MSP430FR2476 MCU	1.8V to 3.6V	3.75mA (max)

HT1621 LCD Screen	2.4V to 5.2V	300uA (max)
Ti CC1101 Transceiver	1.8V to 3.6V	34.2mA (max)

3.1.3.2 External Power Supply

A power supply unit is an essential device that converts AC wall power into low-voltage DC power to charge a device [108]. For our project, the purpose of a power supply unit is to provide a consistent and regulated supply of power when the device needs to be charged. Instead of an onboard design, an external charging station is chosen to reduce the size and weight of the device, promoting its versatility.

3.1.3.2.1 Power Supply Technology Comparison

3.1.3.2.1.1 Linear Power Supply

The first type of AC-DC power supply is a linear power supply. Most linear power supplies work by reducing high-voltage AC power into low-voltage AC power through the use of a power transformer [108]. Then it is run through a rectifier and smoothed out by filter capacitors to obtain DC output power. It is often paired at the end with a linear voltage regulator to improve the stability of the DC output and make it less susceptible to transients [108].

Linear power supplies offer several key advantages. The main advantage is that they are straightforward to design and implement. The number of components is minimal, with no requirement for feedback loops and protection circuits. They also produce cleaner output with less noise and ripple compared to other technologies. However, linear power supplies are not without their disadvantages. They have lower efficiency compared to due to their continuous dissipation of power as heat, and to manage this heat, the use of larger heat sinks is required [112]. The larger heat sink, as well as the requirement for a large transformer due to imprecise regulation, make linear power supplies quite large and heavy.

3.1.3.2.1.2 Switch-Mode Power Supply

The second type is a switch-mode power supply (SMPS). Most switch-mode power supplies first rectify the high-voltage AC power and smoothed before the voltage is stepped down via a transformer [108]. On the secondary side, a diode and a filter is used to provide a stable DC voltage, and a feedback circuit is implemented to control a pulse-width-modulated switch (connected to the primary side of the transformer) that modulates the input voltage on and off at a high rate to generate the desired output voltage [112]. Switch-mode power supplies often utilize an EMI input filter to suppress noise going into the wall and snubber circuits for protection against high-voltage spikes generated by the switching device [114], [115].

Switch-mode power supplies tend to have much higher efficiency ratings due to switching states compared to linear power supplies. The need for a large transformer is no longer necessary, allowing for the capability of a smaller and lighter design. Some downsides of these types of power supplies are their increased complexity. The switch often requires a feedback circuit, bias circuitry, and special snubbing circuits that make

the circuitry more complex. The way these power supplies work by switching naturally induces electrical noise and ripple into the output. This requires additional filtering in both the input and output of the supply [112].

3.1.3.2.2 Power Supply Technology Selection

Linear power supplies are straightforward to build, but are large and dissipate a lot of heat. Switch-mode power supplies are highly efficient and compact, but generate noise and involve a significant amount of components. Both options are suitable for our design, and neither stands out over the other as the best option. But due to the higher efficiency, we will use the SMPS technology. Although the power supply is external, so weight and size are not a high priority, we do not want the charging module to be much bigger than the medical device. In this case, using SMPS technology is beneficial for size reduction.

3.1.3.2.3 Power Supply Comparison Table

	Part	
	Linear Power Supply	Switch-Mode Power Supply
Complexity	Low	High
Efficiency	Low	High
Noise	Low	High
Power Dissipation	High	Low
Size	Large	Small
Decision:	Switch-Mode Power Supply	Higher efficiency and small size

3.1.3.2.4 Power Switching Device

3.1.3.2.4.1 Power Switching Device Part Comparison

3.1.3.2.4.1.1 TNY288

The TNY288 by Power Integrations is an energy-efficient, off-line switcher designed for AC-DC flyback topologies. The chip supports universal AC input, which is between 85 and 265VAC and an output power of between 9 to 14.5W (adapter design), depending on package type. The chip consists of a high-voltage power MOSFET and controller in one device that uses an ON/OFF control to regulate output voltage, eliminating the need for loop compensation. This type of control provides constant efficiency down to very light loads, which easily meets mandatory CEC regulations and EuP standby requirements. The oscillator, inside the controller, incorporates circuitry that introduces a small amount of frequency jitter, which is modulated to 1kHz to optimize EMI reduction for both average and quasi-peak emissions. The TNY288 is a part of the TinySwitch-4 family, and all 7 chips in that family are able to be interchangeable in the same circuit without the need to redesign the circuit.

The TNY288 incorporates various protection features. It contains thermal shutdown circuitry that senses the die temperature and typically shuts down at 142°C with 75°C hysteresis. It has a current-limiting circuit that senses the current in the MOSFET and turns it off if the current exceeds the capacitor-programmed internal threshold. In the event of a fault condition, the chip enters an auto-restart operation that disables the MOSFET until the fault is removed. Line undervoltage is monitored via an external resistor connected to the EN/UV pin and DC line that disables the MOSFET until the current on that pin exceeds 25uA. Optional output overvoltage protection is enabled by an internal latch that is triggered by a threshold current of 5.5mA into the BP/M pin connected to a bias winding.

There are two major design decisions stated in the datasheet, the first involves calculating the primary inductance of the transformer for the maximum output power required. The power delivered to the load is proportional to the primary inductance because the frequency and current limit are all fixed by the chip. Secondly, a design decision is between a 150mW no-load consumption and a 50mW consumption by implementing a bias winding. A bias winding is an additional winding on the secondary side of the transformer that provides power to the chip. The TNY288 does not require this to be powered, but it does use less power than self-bias, resulting in a small no-load consumption. The bias winding is also required to implement the output overvoltage protection, which would protect the load against open feedback loop faults.

3.1.3.2.4.1.2 NCP12400

The NCP12400 by onsemi is a fixed-frequency, current-mode flyback controller featuring the Dynamic Self-Supply feature. This function simplifies the design of the auxiliary supply by activating the internal startup current source to supply the controller. This chip is a multimode controller in which the operating mode depends upon line and load conditions. Under normal operating conditions between 100% and 33% full rated power, the converter operates in a fixed-frequency PWM mode. The fixed-frequency mode operates at either 65kHz or 100kHz and uses a current-mode control where the peak primary current is sensed each cycle and compared against a control voltage. For loads that are between 32% and 10% of full rated power, the converter operates in frequency foldback mode. This mode is activated when the voltage on the FB pin goes below a feedback voltage threshold and begins to linearly reduce the frequency of the internal oscillator. This feature increases efficiency under the light load condition. For loads under 6% full rated power, the converter operates in skip mode. Skip mode begins when the FB voltage reaches an even lower feedback voltage threshold. The chip uses a technique to eliminate the last short pulses in skip mode, which directly increases the system efficiency. For no-load, the converter operates in the low consumption off mode. This mode allows the device to reach an extremely low input power of <30mW.

The NCP12400 features internal overpower protection via an external resistor in series between a sense resistor and the CS pin to generate an offset proportional to the input voltage. The overcurrent protection feature is able to work with any transformer, as it depends only on the current sensing (CS) signal. When an overcurrent occurs on the output, the FB loop tries to draw more power than the controller can handle, so an

internal fault timer gets triggered. This stops the DRV pulses, and the controller is latched off. The timer is reset when the CS pin goes below the maximum setpoint. The NCP12400 also includes a temperature shutdown trip point of 150°C and a typical hysteresis of 30°C.

A major design decision depends on whether we want the Dynamic Self-Supply feature. This feature can only be used in light load conditions; otherwise, the power dissipation on the die would be too great. For normal operation, an auxiliary voltage source is needed.

3.1.3.2.4.1.3 UCC28750

The UCC28750 by TI is a current-mode flyback controller with secondary-side regulation via an optocoupler. It supports universal AC input, between 90 and 265VAC and up to 70W output power. A trickle charge resistor network and an auxiliary winding on the primary side provide the bias to the IC. This IC is a multimode controller as well. Similar to the NCP12400, during light loads, the controller enters a frequency foldback and bursts mode to improve light-load efficiency. In all operating modes, the controller utilizes frequency dithering (also known as jitter), which improves EMI performance. It modulates the primary switching frequency by a small margin to spread the EMI energy, thus lowering EMI peaks.

The UCC28750 power switch provides robust protection features. The first protection feature is overvoltage and undervoltage lockout. The device does not start the switching operation until the input voltage reaches above 15.3V, and will continue to operate until it reaches either 9V or 28V (overvoltage lockout threshold). The second feature is an internal overtemperature protection. The die will become disabled if the internal temperature reaches 160°C and a hysteresis of 20°C. The third feature is a line-compensated, output overpower protection. The FP pin voltage is compared to a generated ramp wave, and when greater, the overpower protection timer increases. If the timer reaches a threshold value, the fault is engaged and disables the device. The next feature is output short-circuit protection. If the CS pin is above the maximum CS threshold during a leading edge blanking time for eight cycles during a short circuit event, the protection is engaged and disables the device. Another safety feature is a programmable over-temperature protection and over-voltage pin by using both an external thermistor and a zener diode. Overvoltage protection occurs when the zener voltage minus the FLT pin voltage crosses 4V.

3.1.3.2.4.1.4 AP3928

The AP3928 by Diodes Incorporated is a universal AC voltage step-down power switcher with a non-isolated buck solution. The device integrates a 700V power MOSFET that coordinates with a single-winding inductor. The peak current and switching frequency continuously decrease as the load decreases, allowing the device to achieve high efficiency performance at light loads. It can achieve a 10W maximum output power and a maximum 600mA rated output current. The output voltage is externally programmed by a resistor network connected to the feedback pin. A no-load power consumption of less than 30mW can be achieved through the use of an external bias and the IC utilizes

frequency modulation to suppress EMI, making it possible to realize mandatory energy and EMI regulations.

The device has multiple protection features to enhance the system's safety and reliability. The overload protection feature triggers via an internal OLP timer up to a threshold count, when the peak current reaches the maximum limitation. It also features short-circuit protection when the peak current exceeds the short-circuit threshold, and resumes operation when the fault is removed. It also has an internal overtemperature protection function that begins to reduce output voltage if the junction temperature exceeds 150°C. The AP3928 can detect open loops when the FB voltage drops below a threshold.

The one missing protection feature of this chip is galvanic isolation. So a mandatory design decision would be to incorporate an isolated DC/DC converter at the output. This isolated converter would provide galvanic isolation of the output from the input. Careful design of this converter would also achieve an appropriate output power conversion. It could step down the 10W maximum output power of the AP3928 into the necessary 5W (5V/1A) required by the lithium-ion charging IC.

3.1.3.2.4.2 Power Switching Device Selection

We have decided to use the TNY288 flyback controller for our switch-mode power supply. The TNY288 was chosen for its simple design, power efficiency considerations, and EMI considerations. To adhere to the 10 CFR 430 regulation, stand-by power must be lower than 100mW. The TNY288 can achieve this through the optional bias winding.

3.1.3.2.4.3 Power Switching Device Table

	<u>Part</u>			
	TNY288	NCP12400	UCC28750	AP3928
Optimal Topology	Flyback	Flyback	Flyback	Non-Isolated Buck
Package	S0-8C, DIP-8C, SOP-12	SOIC-8	SOT-23-6	SO-8
Bias	Self-Bias	Bias Winding	Auxiliary Winding	Internal Supply
Output Voltage	Externally Programmed	Externally Programmed	Externally Programmed	Externally Programmed
Thermal Shutdown	142C (Typ)	150C (Typ)	160C (Typ)	150C (Typ)
Standby Power	<50mW and <150mW	<30mW	N/A	<30mW
EMI Performance Feature	Frequency Jittering, Achieves Class B EMI Limits	Frequency Modulation	Frequency Dithering	Frequency Modulation
Decision:	TNY288		Reasoning:	Simple design,

			Stand-by Power, EMI Performance
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3.1.3.2.5 Rectifier

The role of the rectifier is to convert the AC voltage into an unstable DC voltage. There are two types of rectifiers: half-wave and full-wave. Half-wave rectification eliminates the negative portions of the input sinusoid, while full-wave rectification inverts the negative portion of the sinusoidal wave to achieve a unipolar output [115]. Following the suggestions of the TNY288 datasheet, a full-wave diode bridge rectifier is recommended.

3.1.3.2.5.1 Rectifier Part Comparison

3.1.3.2.5.1.1 DB107

The DB107 is a single-phase 1-amp glass passivated bridge rectifier in a 4-pin EDIP package. It features a low forward voltage drop of 1V, a high forward surge current of 45A, and has a peak reverse voltage rating of 1kV. The operating junction temperature of the chip is between -55°C and 150°C. The average current begins to derate as the case temperature rises above 90°C, and hits 0A at 150°C.

3.1.3.2.5.1.2 ABS210

The ABS210 is a single-phase 2-amp surface-mount glass passivated bridge rectifier in the SOPA-4 package. It has a peak reverse voltage of 1kV and a voltage drop of 0.95V. The average output current is 2A with a peak forward surge current of 60A. Like the DB107, the operating temperature range is between -55°C and 150°C, but only begins to derate current at 100°C, dropping to 0A at 150°C.

3.1.3.2.5.1.3 GBU6M

The GBU6M is a glass passivated bridge rectifier in a GBU package. It has a higher current capability of 6A and up to 175A peak for the surge overload rating. The rectifier has a forward voltage drop of 1V and a maximum reverse voltage rating of 1kV. The operating junction temperature of the chip is between -55°C and 150°C. Without a heat sink, deration begins to drop at 40°C, reaches 1A at 130°C, and 0A at 150°C. With a heat sink, current derating begins at 100°C, reaches 1A at 140°C, and 0A at 150°C.

3.1.3.2.5.1.4 1N4007

The 1N4007 is a single through-hole recovery diode rated at 1A. It has a peak surge current of 30A, a forward voltage drop of 1.1V, and has a max reverse voltage of 2kV. The diode has an operating junction temperature of between -50°C and 175°C. Average current starts to derate at 40°C, hits 50% maximum forward current at 125°C, and 0% at 160°C. Unlike the previous two that come in a bridge configuration already, this device is only a single diode. Therefore, four of these components must be purchased to achieve the diode bridge configuration.

3.1.3.2.5.2 Rectifier Part Selection

The rectifier we have decided to use is the GBU6M integrated bridge rectifier. It has a higher current rating, making it less susceptible to damage than the other two rectifiers

might be subject to. Since it is capable of a higher average forward current, the thermal performance is the best among the four for a 1-amp draw.

3.1.3.2.5.3 Rectifier Part Table

	Part			
	DB107	ABS210	GBU6M	1N4007
Package	4-EDIP	SOPA-4	GBU	Through-Hole Diodes
Max Reverse Voltage	1kV	1kV	1kV	2kV
Avg. Forward Current	1A	2A	6A	1A
Peak Surge Current	45A	60A	175A	30A
Operating Temperature	-55C to +150C	-55C to +150C	-55C to +150C	-50C to +175C
Decision:	GBU6M		Reasoning:	Higher Current Forward

3.1.3.2.6 Linear Regulator

Voltage regulation is a crucial aspect of a power supply unit to ensure a steady and regulated output voltage to the load (our device) regardless of fluctuations in the input [109]. Switch-mode power supplies do not necessarily require the use of voltage regulators due to the use of a reference voltage and a feedback circuit. However, implementing a regulator can improve the independence of load impedance and input variations [117]. Of the few types of voltage regulators available, we need a type that generates low noise and EMI that will ideally not affect the sensor. In this case, a linear voltage regulator will be used.

3.1.3.2.6.1 Linear Regulator Part Comparison

3.1.3.2.6.1.1 LM7805

The LM7805 is a fixed 5V positive linear regulator that supports an output current of up to 1.5A with an adequate heatsink. It is a low dropout regulator with a max line regulation of 0.125%/V and a max load regulation of 1%/A in worst-case scenarios. It has a dropout voltage of 2V and a recommended minimum input voltage of 7.5V to maintain line regulation. It employs features like internal current-limiting, thermal shutdown, short-circuit protection, and safe-operating-area protection.

This IC is designed for fixed voltage applications and the elimination of noise and distribution problems. The typical applications of the LM7805 are industrial power supplies, SMPS post-regulation, measurement equipment, and DC motor drives. Apart from the chip itself, the LM7805 suggests using two external capacitors. The input

capacitor is required if the regulator is located far from the power supply filter, and the output capacitor is optional for improved transient response.

3.1.3.2.6.1.2 MC7805

The LM7805 is a fixed 5V positive linear regulator that supports a continuous output current of 1A and up to 2.2A briefly. It has a maximum line regulation of 0.1%/V and load regulation of 1%/A. This regulator employed multiple safety features such as internal current limiting, thermal shutdown at 150°C, and safe-area compensation.

The MC7805 is designed for fixed voltage applications including local, on-card regulations. Common uses are for automotive and other applications that require an NCV Prefix. The chip uses two external capacitors, one for each port. Like the LM7805, the input capacitor is only required if the chip is far from the power supply filter, and the output capacitor helps improve the transient response.

3.1.3.2.6.1.3 ADP1708

The ADP1708 is an adjustable 5V positive linear regulator that supports a maximum output current of 1A. It is a low dropout regulator with a maximum 0.1%/V line regulation and 1%/A load regulation. The dropout voltage under a 1A draw is 600mV and has a recommended max input voltage of 5.5V. The ADP1708 is protected against damage due to high currents and thermal overload. The IC reduces the output voltage if the output load exceeds 1.5A and shuts down when the temperature of the die exceeds 150°C.

The ADP1708 is designed for high power supply rejection and excellent line and load transient response. The common uses of the IC are memory components, telecommunications equipment, and microprocessor supplies. The ADP1708 uses two external capacitors and a voltage divider network to program the output voltage between 0.8V and 5V.

3.1.3.2.6.1.4 TPS7A7001

The TPS7A7001 is an adjustable 5V positive linear regulator that supports a maximum current output of 2A. It is a very low dropout regulator with a maximum 0.4%/V line regulation and 0.75%/A load regulation. The dropout voltage under 1A is 200mV with a maximum recommended input voltage of 6.5V. The two protection features of this IC are a fixed current limit of 2.1A and thermal shutdown at 160°C.

The TPS7A7001 is designed for very low input voltage and very low dropout voltage applications. Common uses of the IC are in medical equipment, notebook computers, and battery-powered systems. The external components required by the chip are an input and output capacitor, and two resistors to program the adjustable output voltage between 1V and 5V.

3.1.3.2.6.2 Linear Regulator Part Selection

We have decided to use the LM7805 low dropout regulator for the final regulation of our switch-mode power supply. The main reason for this decision is the wide range of input

voltage acceptable by the IC. This gives us the option to have a higher SMPS voltage output to the regulator and achieve sufficient line regulation, and not be restricted to either 5.5V or 6.5V as dictated by two of the other regulators. It is chosen over the MC7805 for its slightly better performance in load regulation.

3.1.3.2.6.3 Linear Regulator Part Table

	<u>Part</u>			
	LM7805	MC7805	ADP1708	TPS7A7001
Type	Linear	Linear	Linear	Linear
Input Voltage	7.5V to 35V	5V to 18V	2.5V to 5.5V	1.425V to 6.5V
Dropout Voltage	2V	2V	600mV	200mV
Output Current	1.5A	1A (Typ)	1A	2A
Line Regulation	0.125%/V (max)	0.1%/V (max)	0.1%/V (max)	0.4%/V (max)
Load Regulation	1%/A (max)	2%/A (max)	1%/A (max)	0.75%/A (max)
Decision:	LM7805		Reasoning:	Wide input range and low load regulation

3.1.3.3 Onboard Power

3.1.3.3.1 Battery

A core goal of our project is to be versatile—modular in such a way that it could fit onto various mounts and inside various casings. One way to support this is by making the system not dependent on external power during operation, meaning the system would be battery-powered.

3.1.3.3.1.1 Battery Technology Comparison

3.1.3.3.1.1.1 Alkaline

The first option for batteries are alkaline batteries. These batteries generate electricity via a chemical reaction inside the cell using two electrodes composed of zinc and manganese dioxide [88]. The zinc undergoes oxidation, releasing electrons into the external circuit and returns to the manganese dioxide, which undergoes reduction by consuming the electrons [89]. Simultaneously, an alkaline electrolyte known as potassium hydroxide (KOH) exists between the electrodes that dissociates into K^+ and OH^- ions that balance the charge generated by the chemical reaction [88], [89]. Due to this chemical composition, alkaline batteries are designed for single-use and cannot be recharged, which is a significant disadvantage towards other options for long-term use [90]. Some manufacturers have made rechargeable alkaline batteries by slightly altering their chemical composition to allow the chemical reaction between zinc and manganese dioxide to be reversible [91]. But these rechargeable batteries have a limited number of charge cycles, ranging from a few dozen to hundreds, depending on usage. Despite the limitations of rechargeability, standard alkaline batteries remain a widely used power source due to being inexpensive and having a high energy density, meaning they provide

a high amount of energy per unit of weight [89]. They also have a low-discharge rate, so they can last for several years without losing a significant amount of charge when stored properly [89]. Alkaline batteries are suitable for low-drain applications, such as remote controls, toys, flashlights and clocks [88], [90].

3.1.3.3.1.2 NiMH

The second option is nickel-metal hydride (NiMH) batteries. Like alkaline cells, these batteries generate electricity through a chemical process, but instead uses nickel oxyhydroxide and a metal hydride as its electrodes [92]. The metal hydride releases hydrogen, which reacts with OH⁻ ions from the potassium hydroxide electrolyte and releases electrons into the external circuit. The nickel oxyhydroxide reacts with water from the electrolyte and simultaneously consumes the electrons, completing the circuit [93]. This reaction occurs when the battery is discharging into the circuit and is able to be reversed, allowing the battery to be recharged. They have a high charge cycle amount ranging from hundreds to thousands of times, which makes them more desirable to other options. NiMH batteries offer high energy density and capacity, enabling strong performance in higher-drain devices. However, NiMH batteries have a high rate of self-discharge and will lose charge even while unused—requiring frequent charging [94]. Some applications using NiMH are wireless devices, power tools, consumer electronics, and more, due to being a reliable, rechargeable battery.

3.1.3.3.1.3 Li-ion

The third option is lithium-ion (Li-ion) batteries. To generate electricity, this battery behaves like the previous two, with a chemical reaction involving two electrodes and an electrolyte between them. Li-ion batteries offer various compositions that make up the electrodes, but often are an intercalated lithium compound and lithiated graphite [95]. The lithiated graphite releases lithium ions through the electrolyte to the compound and simultaneously releases electrons through the external circuit. The compound reacts with the lithium ions and consumes the electrons, completing the circuit [95], [96]. This is another chemical process that is reversible, allowing for the battery to be recharged many times, ranging from hundreds to thousands of cycles. The benefits of using Li-ion batteries are their very high energy density, as they are very light, and their low discharge rate [94], [96]. Due to their high performance, these batteries are expensive to manufacture, making them a more expensive option than others [94]. But their disadvantage is their safety concern. Li-ion batteries can catch fire if they are overcharged or short-circuited, and potentially even explode. They require high-quality standards in manufacturing and external protection circuits to limit these possibilities [96], [97]. Although they are risky, Li-ion batteries are used in many applications, such as laptops, cellphones, and even electric vehicles [97].

3.1.3.3.1.2 Battery Technology Selection

Alkaline batteries were considered due to their low cost, moderate energy density, and widely available sources. NiMH batteries were considered as a rechargeable alternative offering a balance of performance and cost [94]. Li-ion batteries were considered for their high energy density and high performance. After comparing all three options, we selected Li-Ion batteries due to their rechargeability and high energy density. To ensure safe

operation, we will carefully design a protection circuit that will mitigate risks such as overcharging, discharging, and short-circuiting.

3.1.3.3.1.3 Battery Technology Table

	Technology		
	Alkaline	NiMH	Li-Ion
Rechargeable	Limited	Yes	Yes
Energy Density	Moderate	Moderate	High
Self-Discharge Rate	Very Low	High	Low
Cost	Low (Upfront)	Moderate	High
Use Case	Low-drain applications	Medium- to high-drain applications	High-performance applications
Other Notes	Disposable waste issues	Frequent charging required	Safety concerns and requires protection circuitry
Decision:	Li-Ion	Reasoning:	High-Energy Density

3.1.3.3.1.4 Battery Part Comparison

3.1.3.3.1.4.1 14500 Li-Ion Battery

The 14500 lithium-ion battery is a compact, cylindrical cell measuring 14 mm wide and 50 mm long, identical in size to a standard AA battery. But unlike alkaline AA batteries, the 14500 has a higher nominal voltage of 3.6-3.7V, and can reach up to 4.2V at full charge. To prevent permanent damage to the cell, the safe cut-off voltage is set between 2.5V and 3.0V [100]. It generally has capacities ranging from 600mAh to 1200mAh and can be fully charged in 1 to 2 hours and provides a life cycle of about 300-500 charge cycles, depending on usage and quality [100], [101].

14500 batteries are small and lightweight, making them ideal for compact electronics, flashlights, and other devices with limited space [102]. They have a relatively low discharge capacity, usually between 0.5C and 2C, and relatively low capacity, making them better suitable for low-power devices [101]. Since lithium-ion batteries come with inherent safety concerns, we must also look at the safety characteristics of each form factor. 14500s are usually equipped with internal overcharge, overdischarge, and short-circuit protection installed by the manufacturer [101]. Even with these protection circuits, common practice is to use redundant, external protection circuits to minimize safety risks. A benefit of 14500s is their cylindrical metal casings. These casings provide

robust mechanical protection that makes them durable to physical stress and reduces the risk of swelling and leakage even after years of use [103]. Overall, the 14500 lithium-ion battery is an optimal choice if we prioritize a small footprint for our project, but it has the drawback of requiring frequent charging due to its smaller capacity.

3.1.3.3.1.4.2 18650 Li-Ion Battery

The 18650 lithium-ion battery is a cylindrical cell that measures 18mm wide and 65mm long. They are a size bigger than standard AA batteries and, like the 14500, also have a nominal voltage of 3.6-3.7V. The larger size brings a larger capacity, with the majority being between 1500mAh and 3500mAh, which brings the maximum charge time up to 2 to 4 hours, and a life cycle of about 500-1000 charge cycles [104]. Similar to the 14500 cell, the battery can be charged up to 4.2V and has a cut-off voltage of between 2.5V and 3V [105].

18650 batteries are slightly larger and heavier than 14500 batteries, which makes them better for higher power devices that are heavily limited on space. Common uses are for tool batteries, laptops, power banks, and high-performance electronic devices [100], [103]. The safety features of 18650s are nearly identical to the safety features of the 14500s. Manufacturers equip the cells with internal overcharge, overdischarge, and short-circuit protection circuits like the 14500s [100]. They also have the same cylindrical metal casing that protects them from physical stress. Overall, the 18650 lithium-ion battery is an optimal choice for long battery life and long charge cycle life that does not sacrifice much on sizing constraints.

3.1.3.3.1.4.3 21700 Li-Ion Battery

The 21700 lithium-ion battery is a cylindrical cell that measures 21mm wide and 70mm long. This battery is the largest of the previous ones, which makes it have the largest capacity. The 21700 usually has a capacity between 3000mAh to 5000mAh, which takes between 4 to 6 hours for a full charge. Similar to the rest, it has a nominal voltage of 3.6V-3.7V, a maximum charge voltage of 4.2V, and a cut-off voltage of 2.5V [106]. This battery also boasts the longest life cycle, achieving between 500 to 2000 charge cycles depending on usage [104], [107].

21700 batteries are ideal for high-power devices that require a high-capacity battery. Such devices that use 21700s are electric vehicles, power tools, and medical devices. Across multiple reputable brands, the safety performance of this battery is comparable to the safety performance of the 18650 battery with its identical metal casing. However, it's been noted that historically, the 18650 has had better consistency than the 21700 across multiple manufacturers, leading to a higher safety risk perception [107]. Overall, the 21700 lithium-ion battery is an optimal choice for maximizing battery life and output power, albeit with compromises on size and safety.

3.1.3.3.1.5 Battery Part Selection

We have decided to use the 18650 lithium-ion battery for our portable medical device. The 18650 is valued over the 14500 for its higher charge capacity and life cycle, meaning

it can operate longer without charge and would need fewer battery replacements. The 18650 is valued over the 21700 for its smaller size and reputable safety performance.

3.1.3.3.1.6 Battery Part Table

	<u>Part</u>		
	14500	18650	21700
Nominal Voltage	3.6-3.7V	3.6-3.7V	3.6-3.7V
Charge Capacity	600-1500mAh	1500-2500mAh	3000-5000mAh
Charging Time	1-2 Hours	2-4 Hours	4-6 Hours
Life Cycle	300-500	500-1000	500-2000
Decision:	18650	Reasoning:	Ideal capacity, size, and safety performance

3.1.3.3.2 Charging Circuit

Lithium-ion batteries require a precise charging process to ensure full capacity is reached without risking damage to the cell [98]. A popular charging method that maximizes battery life and performance is called the Constant Current Constant Voltage (CCCV) method. This method consists of two charging phases: constant current phase and constant voltage phase [99]. During the constant current phase, a fixed current is supplied to the battery until a certain voltage threshold is reached. The charger then switches to the constant voltage phase to eliminate overcharging and begins to supply a constant voltage to the battery [98]. Current begins to drop during this phase as the battery slowly approaches saturation, finally finishing the charging process [99].

3.1.3.3.2.1 Charging Circuit Part Comparison

3.1.3.3.2.1.1 TP4056

The TP4056 IC is a constant-current/constant-voltage linear charger for single-cell lithium-ion batteries. It charges an external battery at a fixed 4.2V and has a resistor-programmed charge current of up to 1A. It comes in an SOP-8 package, which can be hand-soldered without much difficulty. It has an internal PMOSFET architecture and integrated reverse discharge protection. The chip features two low-power states, one with no input power supply connected and one with. With no input power supply, the chip enters a low current state with a battery drain current of less than 2uA. With the power supply, the IC's battery drain current will be less than 55uA.

This IC features two charge status pins that signal both charging status and charging completion. The chip uses an internal thermal feedback to regulate the charge current to limit the IC die temperature if it gets above 140°C, and terminates if it gets above 150°C. The chip features a TEMP pin that can be externally connected to a thermistor, in which it compares the TEMP pin voltage to an internal threshold and terminates charging if the voltage is above the threshold. An internal undervoltage lockout circuit monitors the input voltage and begins to charge only when the input voltage is 100mV above the

battery voltage. A feature of the TP4056 is that it constantly monitors the battery voltage and will commence automatic recharge if it drops below 4.05V. It also includes a soft-start circuit that will reduce the inrush current at the beginning of each charge cycle, which minimizes the current load on the power supply.

The IC lacks an integrated power path feature or a load disconnect feature. In typical operation, if the system load remains connected as the battery is being charged, the IC may fail to recognize charge termination due to continuous current draw. To resolve this, an external bypass MOSFET can be used to disconnect the load during charge. Alternatively, a bypass MOSFET paired with a zener diode and a resistor can be used to draw current from the DC input, effectively implementing an external power path. This configuration allows the device to operate safely during charge.

3.1.3.3.2.1.2 MCP73871

The MCP73871 IC is a constant-current/constant-voltage linear charger with power path integration for single-cell lithium-ion batteries. The power path feature, enabled by integrated pass transistors, can power the system while independently charging the battery. It supports a maximum charge current of 1A and up to 1.8A total current, including system load. It comes in a QFN package with 0.5mm pin pitch, which is capable of being soldered by hand.

The IC features two charge status pins and a power good pin, each connected to an LED. The two status pins indicate charge status and charge completion. The power good pin indicates the input power supply indication. The IC has thermal regulation that lowers the charge current as junction temperature increases, with thermal shutdown at 150°C. It has a THERM pin that connects to an external thermistor that will suspend charge if the voltage is higher than factory-set thresholds. It also has an internal undervoltage lockout circuit that will keep the charger in shutdown mode until the input supply rises above a given threshold. The IC continuously monitors the battery voltage and will commence automatic recharge if it drops below V_{reg} .

3.1.3.3.2.1.3 STC4054

The STC4054 IC is a constant-current/constant-voltage single-cell lithium-ion charger. The charge voltage is fixed at 4.2V and the charge current can be programmed by an external resistor to a maximum of 800mA. The STC4054 excels in small PCBs with its minimal external component design. No external sense resistor or blocking diode is required, and only uses an LED, capacitor and resistor for certain functionalities.

The IC features one charge status pin that would connect to an LED indicating charging status. It also features an internal thermal feedback loop that will reduce the output current if the die temperature rises over 120°C. It also features automatic recharge when it detects the battery voltage dropping below 4.05V, and a soft start circuit to minimize inrush current at the beginning of each charging cycle.

3.1.3.3.2.1.4 BQ25616

The BQ25616 IC is a highly-efficient, 1.5MHz, constant-current/constant-voltage synchronous switch-mode buck charger with an integrated power path for single-cell lithium-ion batteries. The power path feature automatically selects from the input source, battery, or both to supply power to the system load. This IC is the most customizable as it can be programmed with a resistor to charge a battery at 4.1V, 4.2, or 4.35V and with a current range between 300mA and 3A. Additionally, pulling the OTG pin high enables the boost mode operation, which boosts the output voltage from the battery voltage to a regulated 5V. This can help reduce BOM costs by eliminating the need for a 5V regulator for some of our 5V components. It comes in a WQFN package with 0.5mm pin pitch, which can be hand-soldered.

An external, input NMOSFET can be incorporated into the input pin to establish a 6V gate drive with the ACDRV pin to provide an external overvoltage protection feature. It also includes a battery cell temperature monitoring pin that connects to an external thermistor that will suspend charge if the battery gets too hot. The IC features a built-in charging safety timer to prevent extended charging cycles due to abnormal battery conditions. Some of the protection features are an input current limit (set by an external resistor), overvoltage protection, overdischarge protection, and system overcurrent protection.

3.1.3.3.2.2 Charging Circuit Part Selection

We require operation while charging, which means the IC requires a power path. The MCP73871 and BQ25616 have an integrated power path, and we can add an external circuit to give the TP4056 and STC4054 an external power path. So in this case, any IC is usable. Since we are using a PPG sensor, any charger that introduces noise during charge can degrade SpO2 accuracy, meaning the control topology of the chargers should ideally be linear. Among the remaining three options, the MCP73871 has the highest amount of protection features and features three separate LED charge indicators. For these two reasons, we will be using the MCP73871.

3.1.3.3.2.3 Charging Circuit Part Table

	Part			
	TP4056	MCP73871	STC4054	BQ25616
Control Topology	Linear	Linear	Linear	Switch-Mode Buck
Package Type	SOP-8	QFN	TSOT23-5L	WQFN
Integrated Power Path	No	Yes	No	Yes
Input Voltage	4V to 8V	3.75V to 6V	4.25V to 6.5V	4V to 13.5V
Max Charging Current	1A	1A	800mA	300mA to 3A
Temperature	-40C to +85C	-40C to +85C	-40C to 85C	-40C to +85C

Range				
Protection Features	Overvoltage Protection, Reverse-Discharge Protection, Thermal Regulation, Undervoltage Lockout	Battery Cell Temperature Monitoring, Overvoltage Protection, Reverse-Discharge Protection, Thermal Regulation, Undervoltage Lockout	Thermal Shutdown	Battery Cell Temperature Monitoring, Input Current Limit, Overcurrent Protection, Reverse-Discharge Protection
Decision:	MCP73871		Reasoning:	Linear topology and various safety features

3.1.3.3.3 Protection Circuit

Lithium-ion batteries pose a serious risk, such as fire and explosion, when subject to overheating, short-circuiting, overcharging, and/or other possible damaging elements. In addition to charging circuits, Li-ion batteries are often paired with protection circuits. These protection circuits provide various protection measures that break the circuit via a switch if they detect certain conditions, like overdischarge and overcharge.

3.1.3.3.3.1 Protection Circuit Part Comparison

3.1.3.3.3.1.1 DW01

The DW01 is a single-cell, lithium-ion battery protection IC that comes in an SOT-23-6 package. The IC enables overcharge protection by reversing the OC pin and turning off the charging control MOSFET to stop charging when the battery voltage rises above V_{oc} . It enables overdischarge protection by reversing the OD pin to turn off the discharging control MOSFET, which stops discharge when the battery voltage drops below V_{od} . For discharge overcurrent protection, the IC compares the voltage at the CS pin to V_{ec} and V_{short} , and if higher than either for a given time, the IC will reverse the OD pin to turn off the discharge MOSFET. The charge overcurrent protection works the same way. If the voltage at the CS pin is lower than V_{cha} for a given time, then the charging control MOSFET will turn off.

3.1.3.3.3.1.2 BQ2980

The BQ2980 is a single-cell, lithium-ion protection IC that comes in a QFN package. It features integrated charge-pump FET drivers that provide high-side battery protection. The overvoltage protection is achieved by detecting if the battery voltage exceeds the OV threshold for a certain time, and therefore driving the CHG output to turn off the charging FET. The undervoltage protection occurs when the battery voltage is measured to be below the UV threshold for a given time, then driving the DSG output to turn off the discharging FET. Charge overcurrent protection is achieved by detecting a voltage drop across an external resistor and comparing it to the VSS pin. The IC triggers the CHG output to turn off the charging FET if the voltage drop minus the VSS voltage is lower than the OCC threshold. Discharge overcurrent protection is triggered when the same voltage comparison (as in charge overcurrent protection) is higher than the OCD threshold, and triggers the DSG output to turn off the discharging FET. Some devices in the family have a built-in internal temperature sensor to detect if the internal temperature

exceeds a threshold and thereby drive both CHG and DSP outputs to turn off the charging and discharging FETs.

3.1.3.3.1.3 LC05111CMT

The LC05111CMT is a single-cell, lithium-ion protection IC that comes in the WDFN6 package. It has an internal power MOSFET and integrates the charging and discharging switches, removing the need for external ones and thereby reducing BOM costs. This IC features an overcharge protection by detecting if the battery voltage is equal to or higher than the detection voltage and turning off the charging sequence. For the overdischarging feature, the IC detects if the battery voltage becomes lower than another detection voltage and turns off discharging if it is. The discharge overcurrent protection is triggered when the CS pin voltage becomes higher than the detection current for a given time. The charging overcurrent protection is triggered when the CS pin becomes lower than another detection current.

3.1.3.3.1.4 UCC3952

The UCC3952 is a single-cell lithium-ion protection IC that comes in the SOIC-16 package. It features an on-chip MOSFET that reduces external component count to a single capacitor, and includes a charge pump for reduced power losses. For the overcharge protection, the device will disable charging if it detects the cell voltage exceeding the overvoltage threshold. For the overdischarge protection feature, the device disconnects the load from the battery pack when the battery voltage falls under the undervoltage threshold. The device will remain disconnected until the application of a charger. Discharge current is continuously monitored via an internal sense resistor and turns off the internal MOSFET if a current over 3A persists for over 1ms. The device does not automatically restart normal operation after the overcurrent event, and instead requires the battery pack to be manually removed from the system to reset the fault condition.

3.1.3.3.2 Protection Circuit Part Selection

All four protection chips feature nearly an identical list of protection features, with the BQ2980 having an extra overtemperature protection feature and the UCC3952 not having a charge overcurrent protection feature. The over temperature feature is not an extra benefit as the charging IC has temperature protection. The UCC3952 is nonideal since the IC can not reset itself after an overcurrent event. Out of the remaining three, the DW01 has the most usage and implementation, and the reliability is the reason why we have chosen this IC.

3.1.3.3.3 Protection Circuit Part Table

	Part			
	DW01	BQ2980	LC05111CMT	UCC3952
Package	SOT-23-6	QFN	WDFN6	SOIC-16
Temperature Range	-40C to +85C	-40C to +85C	-40C to +85C	-20C to +70C

Overcharge	Yes	Yes	Yes	Yes
Overdischarge	Yes	Yes	Yes	Yes
Discharge Overcurrent	Yes	Yes	Yes	Yes
Charge Overcurrent	Yes	Yes	Yes	No
Over Temperature	No	Yes	No	No
Decision:	DW01		Reasoning:	Accuracy

3.2 COMMUNICATION PROTOCOL

When working with embedded systems, it is important to understand the various ways that devices can talk to each other to transmit data. This is necessary to have systems, such as displays or sensors, talk to our micro controller to perform the necessary task. In this section, we will discuss the various communication protocols to gain a better understanding of how they work and where they'll be useful. The most common protocols are Universal Asynchronous Receiver/Transmitter (UART), Inter-Integrated Circuits (I2C), and Serial Peripheral Interface (SPI).

Before going into the specific protocols, there is some important background information to know. There are two forms of transmission, asynchronous and synchronous. The main difference is that asynchronous doesn't share processor clock rate while synchronous does share processor clock rate. Synchronous transmission also has three forms: simplex, half-duplex, and full duplex. Simplex is one-way communication, while duplex is two-way communication. Full duplex does two-way transmission at the same time, while half-duplex does not. We also need to take into account what the device allows for. In some cases, the device to use will have a communication protocol in mind to use. Even if a "best-case" protocol does exist, knowing how to interface with common protocols is still useful in the event that we need the knowledge for a particular peripheral.

3.2.1 UART

The first form of communication we will discuss is UART, an asynchronous full-duplex form of device data transmission. This interfaces with two peripherals by "converting data into packets for sending or rebuilding data from packets received" [127]. The packets have a typical formatting, which constitutes the following: one starting bit, from five to nine data bits, one parity bit, and one to two stop bits. The starting bit signals the start of communication, the data bits are the real data being sent, the parity bit is used to "determine if there was a data loss during transmission", and the stop bits signal the end of the data packet [127]. When two devices communicate, they need to configure a few fields, such as "baud rate, same data length, parity bit, and same number of stop bits" [127]. These configurations make sure that both devices are in agreement on how they'll

receive and transmit data. Once the receiver gets this data, they check for any errors to make sure the data has been sent uncorrupted. This is particularly useful for systems where data parity is extremely important. After the receiver checks if any errors have occurred, the data packet is stripped down to the payload data. However, this error detection and addition of bits to packets introduces a ton of overhead for the communication that makes this a slower way to transmit data.

3.2.2 I2C

Inter Integrated Circuits communication protocol is a “half-duplex, synchronous communication protocol” [127]. This means a shared clock signal is needed, and devices can either send or receive data. I2C only needs two signals for communication, those being Serial Data (SDA) and Serial Clock (SCL). As their names imply, SDA is where data is transmitted and SCL is the signal for sharing a clock signal. For I2C, a singular device called the master, which “generates the clock that the” receiving device, called the slave, “uses as a reference for the transaction” [127]. The master device initiates communication with the slave device(s) for both transmission of data or receiving of data. As alluded to, a unique feature of I2C is that it allows for multiple devices to be connected to the same SDA and SCL lines. This is due to I2C requiring unique addresses for each device, which has to be specified when transmitting data. The address is included in the starting bits that the master sends when first initiating communication. If multiple devices exist, when the master sends the start communication, the slave devices that don’t match the address sent “ignore everything from that point onward until a stop condition occurs” [127]. After sending the start and address, we move onto the real data transmission. On every clock pulse, the master sends a bit of data. After every byte that is sent, “the bit that immediately follows is the ACK/NACK bit” which signifies if the byte was properly received [127]. ACK means the byte was properly received, while NACK signifies that something went wrong and a new connection must be made. Assuming all the data is properly sent or received, the master sends a stop condition and ends communication with the addressed device. If a situation occurs where a device needs extra time before another byte is sent, the slave device can use clock stretching to halt data transmission, by “holding the clock line low” [127]. This works since a clock line being high signals that data can be read by the receiving device, the inverse being true for low clock line. I2C is a great communication protocol, since it allows for multiple devices and only two common lines between those devices. The only downside is that communication can be slow since transmission and receiving of data cannot occur at the same time.

3.2.3 SPI

Another communication protocol is SPI. This is a full-duplex, synchronous protocol. Instead of I2C’s two wires, SPI utilizes four signal lines. To send data to peripherals, master out slave in (MOSI) is used. The master device receives data by the master in slave out (MISO) line. Since this form of communication is synchronous, a serial clock (SCK) line is also needed. The last line is slave select (SS) which allows the master device to enable and disable specific devices when transmitting data. When initiating communication, the “slave select line connected to that particular slave needs to be pulled low” [127]. This allows the specific device to be communicated to. During the data

transmission, similar to I2C, a bit transfer occurs on every clock cycle. However, “one bit is transferred from the master to the slave and from the slave to the master” [127]. One way to think about this is a cycle of 8 bits that gets shifted every clock cycle until a complete transfer has occurred. Due to this structure, communication is always two-ways and both devices must send data. If the programmer wants to imitate read-only or write-only, they can utilize dummy bits to send data from one device to the other. If the master device wants to interface with multiple slave devices, the master must “configure the clock frequency that can be supported by the particular slave device it wishes to communicate with” [127]. A strength that SPI has is the speed of data transmission. Protocols like I2C and UART have some defined transfer speed limits, but SPI has no upper limit. I2C is typically maxed at “3.4Mbps in High-Speed Mode” while SPI is commonly used at “over 10Mbps” [127]. For our project, unless the sensor needs extremely high communication speeds, SPI’s advantage of high speed doesn’t seem to be necessary.

3.3 SOFTWARE COMPARISON AND SELECTION

3.3.1 Technology Comparison and Selection (Software)

One of the final components that our measured data must interact with is the software. Without reliable software created, the device won’t be able to turn measured data into readable numbers that display the heart rate and oxygenation levels. To ensure a strong software system is built, we’ll explore the many layers of software that need to be selected to best fit our project goals. Since custom software typically doesn’t come at a dollar cost, we need to keep performance as our number 1 goal. Poorly optimized software can result in increased power consumption and bad results.

A basic part of software development, especially for embedded systems, is where our software will run. In this case there are two choices: Bare Metal Programming and a Real-Time Operating System. Let's discuss a Real-Time Operating System first, since the understanding of an Operating System is important for this section. An operating system is a level of software that controls many parts of the processor hardware and a program’s level of access to the hardware. There are many layers to what the operating system can do, a few important ones are: it “handles task management, resource allocation, ... determines which task runs” based on scheduling managers, enabling “concurrent application designs, ... integrated support for software timers and precise delays” [128]. An operating system manages more granular tasks that a developer would otherwise have to implement manually. This provides an easier development experience and concurrent programming for multiple tasks. A real-time operating system differentiates itself from a normal operating system by being “lightweight” and “specifically designed for managing real-time task executing”. While an operating system gives many benefits, the main drawback is that it forces more overhead from the micro controller. On the other-hand, Bare Metal Programming doesn’t have an operating system to control many granular tasks. It is the job of the programmer to deal with memory management (depending on the language), setting timers, and ensuring data doesn’t get corrupted. Removing the overhead from an operating system is a great benefit though for low-power systems, as “bare-metal is ideal for ultra-low power wearables, ... and compact medical sensors”

[128]. With this in mind, our system will ideally go without a Real-Time Operating System. Our project doesn't require several programs running at once and modern compilers give the programmer many great tools to implement interrupts and timers at precise times.

Another key component of software development is the programming language of choice. There are many languages that each have their use cases and benefits that fit particular tasks. We will discuss more popular programming languages used for embedded systems / software development as they're typically standard. It is important to note that most coding languages can complete the same given task, but specific languages have key benefits. Four of the most common languages to use for medical devices are C, C++, Java, and Python. An important concept to know is that of low-level languages and high-level languages. A low-level programming language is typically classified as being closer to machine language instead of readable human language. C is a great example of a low-level language. This is caused by having the programmer control memory allocation [129]. Having the programmer control memory allows for minimal resource usage and quick code run times. Another low-level language is C++, but differentiates itself from C by being object-oriented. In simple terms, object-oriented programs allow for the declaration of classes to represent several instances of data. This also encourages "code reusability and modularity, which is beneficial for large-scale projects" [129]. Both C and C++ have great performance, but the tradeoff of being a low-level programming language is that they're typically more difficult to develop for and they have issues if the developer doesn't manage memory correctly. In the worst case scenario, the program may not run at all if proper memory management isn't given. That is where high-level programming languages come in. The trade-off of less performance but quicker development time is the main benefit of choosing a high-level language such as Java or Python. Java has the benefit of being object-oriented and being "suitable for applications requiring high data protection" [129]. Python on the other hand has a vast "ecosystem of libraries" that can enhance developer experience with an easier environment to develop software in [129]. Out of these four options two stick out the most, those being C and Python. Since this project isn't large-scale for software, there is no reason to include object-oriented programming practices. Furthermore, C and Python can be used as object-oriented languages with enough work. At this point, choosing between the two comes down to the project goals. Since performance is our a-Tyler, C is the most reasonable choice.

3.3.2 Part/Product Comparison and Selection (Software)

	Technology	
	C	Python
Simplicity	Medium	High
Language Speed	High	Low
Libraries	Medium	Very High

Compatibility with MCU	On-board	None
Decision: C	Reasoning:	C is much faster than Python, and is directly compatible with our MSP430 chip

If we really wanted to, it could be possible to use python with our project. However, it would require transmitting raw data from the sensor onto a different MCU that supports python which isn't necessary. With enough work, C can do everything that python would be needed for in this project.

4. STANDARDS AND DESIGN CONSTRAINTS

4.1 CRITICAL STANDARDS

4.1.1 OLGA Package

The OLGA package is a packaging standard set by Maxim Integrated (Analog Devices) to integrate LEDs, ASICs, or both into one component. OLGA stands for Organic Land Grid Array [OGLA]. Organic refers to the substrate material the die is mounted to. Organic substrates cost less and have better joint reliability since the material more closely matches the PCB's thermal expansion [3]. All packages of this standard are leadless; the leads are completely flat and fully hidden underneath the package, very similar to a QFN or DFN package with recessed terminal ends [OGLA].

Analog Devices recommends using Non-Solder Mask-Defined (NSMD) pads for the PCB so that there is a larger metal area for solder to attach to the pads on the package. The Organic Solderability Preservative (OSP) surface finish for the PCB is recommended for greatest reliability when the device is dropped; however, Electroless Nickel Electroless Palladium/Immersion Gold, Electroless Nickel/Immersion Gold, Immersion Silver, Electrolytic Nickel/Gold, and Immersion Tin can be used as finishes as well [61].

The OLGA package can be mounted on either a regular PCB or a flex PCB. For a regular PCB, it is recommended that thin boards are used. For 1.0-1.4 mm thick OLGA packages a board thickness of less than or equal to 0.6 mm should be used. For packages greater than 1.4 mm thick, the PCB board should be less than or equal to 0.85 mm thick. The reason is, thicker boards have more material to expand or contract when surface-mount soldering the package to the board, which could potentially cause failures [OLGA, 3].

Per the JEDC specification JSTD020D.1, all Maxim OLGA meet the MSL3 standard. Parts are shipped in a dry pack, with desiccants and a humidity indicator card. They are pre-baked before shipping to release moisture. If the card has turned pink, or the packages have been exposed longer than their lifetime in a factory floor environment, they must be rebaked for 48 hours at 125° C. All OLGA packages contain tiny vent holes to improve reliability and sensitivity to moisture. These holes must not be blocked during soldering to the PCB. To avoid blocking the vent holes, a Type 3 or finer paste is recommended for 0.5 mm pitch packages. Specifically, Analog Devices recommends SAC305 paste. During reflow, they suggest a nitrogen purge. Flux cleaning and rework are not recommended for these packages since moisture and materials can flow into the vent holes and cause damage, and also because they are susceptible to mechanical and moisture damage [61].

Analog Devices also provides recommendations for stencils, pick and place machines, and reflow ovens. The stencil should be 100 µm thick, laser-cut with electropolish, have smooth-walled apertures with rounded corners and trapezoidal cross-sections, and the aperture should be 25 µm smaller than the PCB pad on all sides while also conforming to the industry-standard area ratio of greater than 0.66. The pick and place machine should have 0.05 mm accuracy. Using package outline or lead position methods are both viable

options for placement guidance. The nozzle/vacuum cup should be made of antistatic rubber, pick up the package by its center, the suction pressure should range from -60 kPa to -95 kPa, the gap between the nozzle and the glass when picking up the component should be 0.1 mm, and the bond force of the machine must be 1 N. Finally, the reflow oven should be a forced convection oven with nitrogen. Temperature uniformity ideally should be within plus or minus 5° C. The ramp-down rate should be slow to minimize stress on the package. A table is provided in the OLGA information documentation (see [61]) for the recommended lead-free reflow profile [61].

4.1.2 FCC Part 15

FCC Part 15 contains regulatory standards from the US government on the use of radio frequency devices, including intentional radiators, which characterizes the radio frequency operations of our prototype. We will have to ensure that our prototype operates in compliance with these guidelines. We decided to utilize digital modulation in the ISM band to narrow down the number of standards that we must attentively apply for our use case. Specifically, this allows us to take cues from Part 15.247, which covers operations within 902-928MHz for a digital modulation system, if our 6dB bandwidth is greater than or equal to 0.5MHz. Under Part 15.247, we must ensure that our maximum output power as measured at the SMA port is no greater than 30dBm. Furthermore, we cannot allow our antenna to produce more than 6dBi gain. If our digital modulation system exhibits a 6dB bandwidth under 0.5MHz, we can instead turn to Part 15.249. However, this drastically reduces the allowable EIRP to approximately -1dBm. For this reason, we will opt to align our prototype with Part 15.247, which Ti provides guidance on with regards to the CC1101 [84].

One possible digital modulation setup that complies with FCC Part 15.247 begins with selecting the GFSK modulation scheme (MDMCFG2.MOD_FORMAT = 01). Using SmartRF Studio, we can tune the data rate and deviation until the measured 6dB bandwidth on a spectrum analyzer meets or slightly exceeds 500kHz. Ti advises enabling preamble and sync words to maintain packet synchronization when higher deviation increases instantaneous frequency swing [84]. Calibration must follow every major frequency change. Writing SCAL to the STROBE register will force PLL re-alignment, ensuring stable channel spacing. During transmission, firmware asserts GDO0 to indicate packet completion, at which point the device may return to IDLE or SLEEP to save power.

On the development board receive side, interrupt-driven wakeups on GDO2 allow immediate decoding of inbound packets without continuous polling. Identical register settings must be utilized on the receive side, except that MCSM1 and MCSM2 are configured for continuous receive. Compliance must be ensured by verifying modulation bandwidth, output power, power spectral density (PSD), and out-of-band suppression. The 6dB bandwidth should be measured using a resolution bandwidth (RBW) less than 1% of the emission bandwidth, tracing the frequency points where the amplitude falls 6dB below the maximum. For a CC1101 configured for 500 kbps GFSK and ± 150 kHz deviation, the measured 6dB bandwidth is roughly 600 kHz, which satisfies the criteria outlined by Part 15.247 for 6dB bandwidth. Part 15.247 limits the average PSD to 8 dBm

in any 3 kHz segment. Since the CC1101 in our configuration outputs less than 10dBm conducted, the PSD requirement is naturally met. Finally, regarding spurious emissions outside of the 902–928 MHz, Part 15.247 requires these to be at least 20dB below the in-band fundamental. The CC1101 already suppresses second and third harmonics by more than 40dB.

FCC Part 15 also relates to our switch-mode power supply, which is classified as an unintentional radiator due to the high-frequency switching that can unintentionally radiate electromagnetic interference. Under Part 15, our SMPS must comply with strict limits on both conducted and radiated emissions as a Class B device. Under Part 15.107, the radio frequency voltage that is conducted back onto the AC power line on any frequency within the 150kHz to 30MHz band shall not exceed a quasi-peak conducted limit of 56dBuV (strictest) and average conducted limit of 46dBuV (strictest). Under Part 15.109, the field strength of radiated emissions at a distance of 3 meters must not exceed 100-500uV/m depending on the frequency of emission. The datasheet of the TNY288 states that with the recommended input EMI filter and the integrated frequency jitter of the semiconductor device, the circuit will meet these standards.

4.1.3 IEEE C95.1-2019

Titled “IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz,” this standard defines the constraints that apply to RF radiators in terms of human exposure safety. It does not regulate how transmitters utilize the spectrum or handle interference. Instead, it sets limits to ensure that electric, magnetic, and electromagnetic fields emitted by transmitters do not exceed levels that could cause harm to people who may be exposed to them.

The standard distinguishes between restricted and unrestricted exposure environments. Restricted environments are occupational settings where workers are trained and aware of potential radio frequency exposure. Unrestricted environments include all other scenarios, including public operation (which characterizes the operation of our prototype).

At low frequencies, between 100kHz and 5MHz, the main risks are nerve/muscle stimulation and biological heating, so the limits are expressed in terms of internal electric fields or contact currents [86]. In the RF and microwave range, the dominant hazard is reduced to simply heating of biological tissue. Between about 5MHz and 6 GHz, the relevant metric for safety is the specific absorption rate (SAR), which measures absorbed power per unit mass of tissue in W/kg. Above 6 GHz, the energy is deposited so superficially that power density at the body surface becomes the limiting metric.

Since we are operating in the ISM band with a target frequency of 915MHz, we will focus on the exposure limits in terms of SAR. Localized SAR limits apply to smaller regions such as the head, torso, and limbs. The document specifies limits averaged over 10 grams of contiguous tissue for short-term exposures of six minutes. Local exposure limits for the head and torso are 2 W/kg in the unrestricted case, while limits for the limbs are 4 W/kg [86]. Ultimately, we will have to simulate the SAR utilizing an FDTD solver

once the appropriate geometry has been selected if we want to maximally assure that the device is safe to operate for long periods of time in public in the PCB housing. That being said, the device is very likely to be compliant due to its low power output, and if issues arise in our SAR simulation, we can simply add a layer of physical separation between the device housing and the user to reduce SAR.

4.1.4 10 CFR Part 430

The U.S. Code of Federal Regulations, defined in 10 CFR Part 430, mandates that all external power supplies (EPS) entering the U.S. market must meet a minimum energy efficiency level depending on output power. Our SMPS qualifies as a Class A direct operation external power supply that is subject to low-voltage requirements. Under 10 CFR Part 430.32(w), the efficiency standard mandates that the no-load power consumption does not exceed 100mW for EPS under 49W. For power supplies greater than 49W, but lower than 250W, the maximum power consumption rises to 210mW. For anything greater than 250W, the maximum power consumption is less than 500mW. Meeting this requirement would put our power supply into the level VI efficiency class.

Our power supply will output 5V at a nominal current output of 1A, with a maximum of 2A. This means our power supply will fall under the 49W standard, and should have a no-load power consumption of under 100mW. At standard 120VAC, the power supply is predicted to consume 35mW, and have an efficiency of above 83%. This no-load power consumption is well within the 100mW maximum limit dictated by 10 CFR Part 430. This is accomplished through the use of a bias winding to power the IC, which in comparison would change to 150mW when self-biased. Additionally, the device also utilizes an ON/OFF control logic that maintains high efficiency down to very light loads, which is ideal to meet this mandatory regulation [119].

4.1.5 IEC 62304

To meet the software safety standards of medical devices, we can look towards IEC 62304. This standard provides three classifications of software depending on the level of risk the medical device can impose. A class 1 (or class A) product is a “low-risk device not intended to support or sustain life” [131]. Examples of this can be something like a bandage or wheelchair. For class 2 (class B), these are “intermediate-risk” devices that can come into sustained contact with a user, where a medical worker needs training to use the device [131]. A good example for something like this is a blood pressure cuff. Our final category, class 3 (or class C) is reserved for “high-risk devices designed to sustain or support life” [131]. Defibrillators count for this high risk class. For our project, we can safely say that our device on its own is not intended to sustain life. It only provides medical readings of a patient's oxygenation and heart rate. However, this doesn't mean we are class 1. If our device provides critical misreadings, to the point where it would force the user to seek professional medical assistance, that is the fault of our device. Therefore, a more realistic group for our device would be class 2. Despite not directly sustaining a patient's life, misreadings could lead to undesirable outcomes.

Grouping products based on class isn't the only purpose of IEC 62304. The standard also covers the software life cycle, documentation, verification/validation to confirm that the

software works as intended, and many more. When developing our software, we must provide clear documentation for what is going on under the hood. Additionally, the software is developed in “a systematic manner, with a focus on patient safety and effectiveness” [131]. As we are developing the product, we must also undergo risk assessments to ensure that potential hazards do not arise. To validate our program, we can use online tools to test our process, making sure our device serves its intended use. One way we were planning on testing the effectiveness of our product was to compare it with other pulse oximeters to see how we compare. Another task for us to keep in mind is the labeling on our device. Our team has already been thinking about the necessary labeling, but it is good to have a reminder on what needs to be done, as the standard requires clear and accurate instructions.

4.1.6 IEC 60601

IEC similarly has standards for the safety of medical electrical equipment. The type of equipment this standard falls under are as follows: “products that transfer energy ... including battery operated devices such as thermometers, infusion pumps, endoscopy cameras, and specific types of imaging equipment” [132]. We can safely assume our device falls under this category. One key element of this standard is the essential performance area. This highlights functions that “if not performed correctly, could harm the patient or user” [132]. One way this applies to us is through our PPG sensor. To get reliable readings, our sensor must apply constant pressure to the user’s finger. This pressure must be good enough to ensure a good reading, but not too much to where we cut off circulation to the finger. Similarly to the last standard, there are different classifications of devices known as ‘types’. The three types we need to worry about are Type B (Body), Type BF (Body Floating), Type CF (Cardiac Floating). We can safely eliminate Type CF from our device since we do not make physical contact with the heart or bloodstream. Most likely, we fall under Type BF, which is when our device has “some conductive contact with a patient, either long-term or medium contact” [132]. Since we need a user to maintain sustained contact with our device, we can safely assume the device falls under Type BF. The last type to go over is Type B. These are typically not conductive devices towards the patient, such as hospital beds. As we assume Type BF, we must provide a solid degree of protection against electric shock. One way we plan on doing this is to separate the patient from any direct contact with electrical components. This can include 3D printed housings, see-through panels to cover components that cannot be covered, and ensuring all our electrical components aren’t exposing anything conductive.

4.2 CRITICAL CONSTRAINTS

4.2.1 Noise Handling and Digital Signal Processing of the PPG Signal

As mentioned in the technology research section of the document for the PPG sensor, the analog current signal measured initially by the photodetector is in the nano-ampere range. This is obviously extremely difficult for a project of this scope to deal with. Also, the sensor output in-general is susceptible to so many forms of noise. Designing the circuitry to convert the photodetector signal into something readable while also minimizing interference is so complicated it would be a project by itself. So, a PPG sensor

component with as many features as possible integrated into one chip that is also solderable to a PCB had to be found. No PPG sensors are available on the market with every single feature integrated that the project needs. However, the MAX30101, MAXM86161, and the MAX86916 contain many of the components and analog processing features we need, plus some extra. Specifically, the MAX30101, the sensor used in this project, contains a built-in temperature sensor as an extra feature to potentially be used by algorithms to achieve more accurate measurements.

The MAX30101, MAXM86161, and the MAX86916 all convert the analog signal into digital data stored in an internal FIFO, readable by a microcontroller or other computing device. But, none of them are capable of processing the raw data into meaningful data; it is expected that this is done by the microcontroller. The algorithms needed to interface all the features, obtain at least pulse and SpO₂ measurements, and handle noise from sources like motion are all very complex and outside the scope of this project. Fortunately, Maxim Integrated (Analog Devices) makes the MAX32664, which is a chip that contains the embedded firmware and algorithms necessary to effectively utilize the MAX30101 [62].

Essentially, due to the difficulty of getting data from a PPG sensor, the project is constrained to use the MAX30101 and the MAX32664. This presents a difficulty as the package options for these devices are not hand-solder friendly. Since the sensor and other peripherals for it are supposed to be contained in small devices for wearables or other applications, the packages are made to take up as little area as possible. The MAX30101 (and the other two sensor options) is only available in an OLGA package with two rows of seven leads and a lead pitch of 0.8 mm. The largest package for the MAX32664 is a 3x3 mm 24 pin QFN with a 0.4 mm lead pitch. Both of these packages are very challenging to manually solder. Also, since the MAX30101's package cannot be reworked due to the vent holes, soldering it correctly to the board on the first try is paramount. Luckily, the MAX30101 and the MAX32664 do not need to be on the same board since they communicate via I²C [62]. So, to avoid the soldering complexity of one chip increasing the other's complexity, the chips should be placed on separate PCBs. More specifics about sources of noise and interference is included in the PPG technology research and part selection portion of this report.

4.2.2 Power Draw

A theme that has been explored a few times so far is the amount of voltage and current our components are drawing to execute their task. This is a critical section to pay attention to, especially since a major goal is to be a portable, battery powered device. Having efficient designs and parts will contribute towards our desires of making the device last for a significant amount of time on a battery. The components that contribute the most towards power draw are: our selected MCU, the display, our PPG sensor, and the RF module. To make sure our MCU can draw as little power as possible, we must be able to utilize a chip that supports various low-power modes. During the research portion, we determined that an MSP430 chip, specifically the MSP430FR2475 would be the best choice for our goals. This chip not only supports the low power modes that we need, but also supports all the communication protocols and pins that we'd require to connect

everything together. For the specific chip we chose, we can see averages of 135uA per MHz on ultra-low-power modes with a maximum of 4.1V input. This should give us .5mW of power draw per MHz assuming maximum voltage draw. Another component that tends to draw a lot of power is the LCD and the display controller. For this project, we chose the HT1621 LCD controller since it was able to interface with the desired display type. Our specific board takes a 5V source with three different areas of current draw depending on the setup. The on-chip RC oscillator takes at maximum 600uA of current draw. For the crystal oscillator, 240uA of current is needed. Finally, the external clock source will draw 400uA at max. Assuming maximum conditions, we draw at most 600uA of current for the display, 300uA being the typical range. At the worst conditions, we use 3mW of power for the display system. That leaves us with two systems left, the PPG sensor and RF module. For our RF module, the CC1101 system also allows for a low-power mode with it during sleep mode, drawing 200nA of current. Assuming we connect the CC1101 directly to a battery, it'll draw 3.6V at 17mA for Rx and 34mA for Tx. Since we are planning to transmit data, we can expect a maximum power draw of 61mW for receiving and 122mW for transmission. As for the PPG sensor, there are two components to consider. We have the actual sensor part, and the algorithm chip in case we need to use it. The sensor chip has stated on its data sheet that it can utilize a low power mode to draw less than 1mW of power. The algorithm chip has a voltage draw of 3.63V and total current for all digital pins combined being 100mA. With this, 363mW of power would be needed for the algorithm chip if needed. If we are to assume maximum power draw for all parts simultaneously, even if not realistic, we could see <500mW of power draw. This is also assuming that we are constantly transmitting using RF, which doesn't need to be an action that happens constantly. With this level of power draw, we can be comfortable knowing that we are operating as a low power system. Additionally, there are several ways we can lower the power draw of our system. Turning off RF when not needed is one way, having an optimized software setup can help, and dimming the brightness of our display all can have a positive effect when building our low-power system. Plus, the software design will have implementations in mind to keep the power draw low.

4.3 REMAINING STANDARDS

4.3.1 MSL Standard

The MSL (Moisture Sensitivity Level) is outlined by JEDEC, a standards organization for the microelectronics industry [63]. Specifically, this standard is described in the J-STD-020F. The J-STD-020F identifies classification levels for non-hermatically sealed surface mount components based on their moisture sensitivity that way the surface mount components can be handled, packaged, and stored properly. Moisture can work its way into non-hermetic surface mount packages, which can cause damage to the device during solder reflow and/or repairs. Specifically, vapor pressure when the component is heated can cause delamination of the package materials, internal or external cracks, bond damage, thin film damage, wire damage, and damage to the die. In severe cases, the pressure can cause the package to crack open with an audible pop; this is known as the "popcorn phenomenon" [64].

Eight MSL levels are defined. MSL1 has unlimited floor life, which is the amount of time the component can be outside of a dry environment before soldering. Level one (MSL1) has unlimited floor life at conditions less than or equal to 30° C and 60% Relative Humidity (RH). MSL1 means the device is moisture insensitive and no special storage pack is required. MSL3, the MAX30101's rating, has a floor life of 168 hours at less than or equal to 30° C and 60% RH. Moisture sensitivity levels ranging from 2 to 5a have to be dry packaged in accordance with standard J-STD-033, since they are deemed moisture sensitive. MSL6 is deemed extremely moisture sensitive and has a floor life that is described on the label of the product or has no floor life at all in conditions less than or equal to 30° C and 60% RH. Customers must be advised of its classification if shipped. The supplier also has to include a warning label showing that the component must be either socket mounted, or baked within the time on the label before soldering [64].

4.3.2 RoHS Standard

RoHS is a standard set by the European Union and the acronym stands for Restriction of Hazardous Substances in Electrical and Electronic Equipment. It is a standard enforced by law that aims to protect people and the environment from the rapidly growing stream of electronic waste; waste that may also contain hazardous substances. RoHS accomplishes this by restricting the use of hazardous substances in electronics. The substances it restricts are cadmium, hexavalent chromium, lead, mercury, polybrominated biphenyls and polybrominated diphenyl ethers, bis (2-ethylhexyl) phthalate, butyl benzyl phthalate, dibutyl phthalate, and diisobutyl phthalate. All electronics have to comply unless explicitly excluded [65].

The RoHS Law/Standard sets out requirements for prevention of mistreatment of hazardous substances, scientific and technical progress, manufacturers, authorized representatives, importers, and distributors. Some of the notable requirements are that manufacturers must keep technical documentation and the EU declaration of conformity for 10 years after the electronics have been placed on the market. Manufacturers must ensure that series production of items must remain in conformity. Also, they must keep a record of product recalls and non-conforming electronics; they must also keep distributors informed of this as well. Electronics manufacturers must ensure that there is some form of serial or batch number associated with the individual products, and some way to contact the manufacturer. Importers can only place electronics on the market that comply with this standard, and beforehand they must ensure that the proper conformity procedure has been carried out by the manufacturer, the manufacturer has technical documentation, and a number of other things. Importers must also place their name and contact information with the individual electronics. Distributors have to ensure electronics comply with the RoHS directive and that associated technical documentation is in a language understandable by the consumers and end-users that product is being marketed to. All handlers of the electronics are required to ensure conformity, otherwise they must take action to bring it to conformity by informing the relevant authorities and/or withdrawing and recalling it from the market [66].

4.3.2 IEC 61000-4

The IEC 61000-4 is a collection of electromagnetic compatibility standards by the International Electrotechnical Commission. This set of standards is not mandatory; however, any good and safe design should meet them. The first standard of note is the IEC 6100-4-2, which is the electrostatic immunity test standard. This standard provides four severity test levels for both air discharge and contact discharge. For the air discharge, it starts at level 1 at 2kV, and goes up to level 4 at 15kV (with different humidity levels). For the contact discharge, at level 1, the contact discharge is 2kV, and goes up to 8kV at level 4. The AC/DC converter design I am using with the TNY288 states that it passes the 15kV air discharge test and the 8kV contact discharge test. These two test results adhere to the level 4 requirement dictated in IEC 6100-4-2. The way the design achieves this is by using a Y capacitor and a spark gap that connects the HV and LV sides of the PCB (as well as other trace placement considerations). So as long as we follow the component placement recommendations, our design should pass the tests as well [118].

The second standard of note is the IEC 61000-4-3, which is the electrical fast transient burst immunity test standard. This tests the device on whether or not it can withstand fast, repetitive transients/bursts in signal, power, and earth connections. For power supply terminals, there are 4 test levels ranging from 500V to 4kV with a repetition rate between 5 and 100kHz. The TNY288 reference design tests at 4kV at different rates between line and neutral wires and passes all tests. This means that the design will meet the IEC 61000-4-3 standard [118].

The third standard of note is the IEC 61000-4-5, which is the surge immunity test standard. This tests the device on whether it can handle unintentional reception of electromagnetic energy, which may cause damage to equipment. This standard has 5 levels that cover a voltage range of 25V to 4kV. The TNY288 reference design explicitly states that it meets the class 3 standard of IEC61000-4-5. Class 3 tests the device at a voltage of 2kV, and the device passes all common mode and differential mode tests [118].

4.4 REMAINING CONSTRAINTS

4.4.1 3D Printability

Making cases for devices on a small scale like this project typically require plenty of hand machining. Also, if a mistake is made in the design or machining process, new materials have to be sourced and remachined in most cases. This can cause many delays as it is easy to make minor mistakes when designing new things. Being able to simply 3D print parts out of plastic simplifies these issues as each printed part only costs fractions of cents to a few cents with a standard printing filament. This means if the design needs to be tweaked or a mistake was made, the part can just simply be reprinted at little cost of money and time. The cost of reprinting is definitely much less than having to resecure access to a drill press, bandsaw, etc. This fact leads to the next benefit, 3D printing allows for the creation of complex parts without the need for dangerous tools or expertise knowledge.

However, there is no such thing as free lunch. The Fused Deposition Modeling 3D printer used for this project prints layer by layer. Since each layer needs to be stacked on the previous, the printer cannot print anything in air, it must have something underneath to support it. The printer is able to do small overhangs as the cooling nature of the printed filament allows the printer to essentially bridge over gaps or stack layers like bricks in a Corbel Arch. However, this is not recommended for high tolerance parts as there is always a little excess drooping. Printing supports is a common technique that leverages the bridging capability of the printer to print large overhangs. But, this has worse tolerance issues because there is still bridging and the printed supports, which also fuse to the model, generally leave excess plastic behind when broken off. Of course the parts can be filed or sanded down after machining. Nevertheless, the best course of action is to design the parts so there are no overhangs, or at the very least they are minimized and the tolerance error is accounted for in the CAD, to print more cleanly and accurately while also removing the time cost of sanding and filing.

Three dimensional printing introduces many more constraints, such as the accuracy tolerance of the printer itself, but these are too numerous to include here; and, they are either heavily printer-specific, or they are common among all machining methods. A final constraint worth mentioning, though, is the print size limitations of the printer. The build plate and build height are only so large, so the entire PPG device must be made with smaller parts than can be made of plywood or sheetmetal; thus, also constraining the size of the PCBs. Moreover, the larger the print, the greater the chance of warping of the part. Warping can be minimized through other techniques, but in-general, it is just simply better to avoid too large of parts when possible.

5. APPLICATION OF AI TOOLS

5.1 ETHAN DENNER'S APPLICATION OF AI

5.1.1 Limitations, Pros, and Cons of AI Use - Ethan

AI is a relatively new tool that gets more powerful everyday. Currently, AI is limited to chat windows, but it is capable of generating text, videos, sounds, code, and is capable of doing advanced computations. Also, some models have an agent capability, which means the AI is capable of doing tasks for the user; however, these agents are still in a very rudimentary stage, and thus, are not very useful at the moment. Different AI models have different capabilities; choosing the right one for the right task is crucial. As mentioned before, AI is still a new tool. This means AI models are still prone to glitches and inaccuracies. Another aspect is that companies, in a race to produce the best model, troubleshoot issues and optimize their AI models differently, even if the AI models are supposed to share the same purpose. This effectively creates a vast sea of models to choose from, each with their own quirks. Another limitation of AI is the cost. There are free models, but they are generally less powerful than the more capable models. A company providing an AI service also has to provide the computational power. For more demanding computational tasks, companies limit consumer use by enforcing a paywall. This paywall almost always comes in the form of a subscription or, on top of that, paying for each computation by paying for tokens. AI is still prone to mistakes whether it is the paid option or the free option, so it is much better to use the free version. This just means the user must be skilled in identifying the weaknesses and errors of their preferred model, and be able to adapt accordingly.

5.1.2 Examples of AI Use - Ethan

5.1.2.1 Research

Currently, research is the greatest strength of web-based AI platforms like Gemini because the model is not required to know the information, it only has to be effective at paraphrasing existing, reliable information. This is an extremely effective principle since it effectively allows a user to search the entire web in a matter of minutes and get a really large and dense pool of information that they could not get just from reading a few websites.

To leverage this capability of AI to the best effect, Gemini's deep research function was used. What this does is it takes a prompt from the user, generates a research plan that the user can edit if they wish, then spends about ten minutes searching the entire web for information about the prompt, and finally outputs the information into a long report complete with citations for almost every sentence and the accompanying citation list with links. Because concepts and information about PPG devices are complex and very numerous, the deep research feature was used to speed up research to make it easier to hit deadlines. The deep research report was used in two ways: first to paraphrase then verify, and second to identify sources first then paraphrase.

The first method, paraphrase then verify, was used to research the Dual Wavelength PPG. The report was first generated. Next, the information in the report was blindly accepted as factual and paraphrased to condense all the relevant information, making it more suitable for this project's report. Finally, each paraphrased sentence was meticulously verified for accuracy by comparing it with the original report to identify which sources would best support the paraphrased information. This process took a long time, but the information gathered was extremely dense and thorough. It would have taken even longer to find that level of knowledge manually. See **Appendix B, B.1.1.1** and **B.1.1.2** for the report that was used for this method.

The second method, identify sources then paraphrase, was implemented for the research on Triple Wavelength PPGs in an effort to speed up research while preserving informational density. This method involved generating the report, same as method one, then reading through it in its entirety. While reading through it, the citations attached to the relevant info are noted down. Each time a source is mentioned, it is tallied. What this creates is a distribution of critical sources to view where the ones that should be read first have a higher amount of tallies. Finally, the sources are read through and everything else follows standard researching techniques. Doing this method did not significantly reduce the research time, however, it did reduce research exhaustion. The utilization of the AI report to identify sources ensured only the maximum amount of critical papers were read through for information. Because a lot of the facts in these papers overlap, allowing less to be used for the same density of information achieved in method one.

An important note is that the second method was tried on the Multi-Wavelength PPG research. However, the AI confused the yellow color Jaundice causes with it being the wavelength used to detect Jaundice. The reality is, green is used to detect Jaundice. Furthermore, several glitches were noticed in the report, such as sentences that abruptly stop mid-way through. It was clear that the report was untrustworthy altogether and so it was not used. The nature of the errors also indicated that the AI would not be able to properly identify correct information regarding the advanced wavelengths, so the research was performed manually. See **Appendix B, B.1.1.3** and **B.1.1.4** for the example of the bad report. With the limited available information on the advanced wavelengths, the manual method of research ended up being the fastest method to complete the Multi-Wavelength PPG's section. In other words, AI is beneficial for researching information with a vast variety of sources, but much less useful for research where supporting materials are scarce.

5.1.2.2 Flux AI Agent for PCB Design

Flux.ai is a company that provides a browser-based eCAD service. Their main selling point is an integrated AI agent that is fully capable of designing a manufacture-ready PCB from scratch based on prompts provided by a user. This would make it an absolutely powerful and dominant program if the agent works properly. The reason being, it removes a lot of the barriers to entry for hobbyists and beginner designers, and it benefits more experienced engineers because it would remove a lot of the busy work. For this project, it would simplify PCB design and ensure no design mistakes cause setbacks. This is why the Flux agent was tested.

There is a reason the agent's capabilities have not been confirmed definitively yet; there is no free lunch. Flux engages in the growing dystopian trend almost every company participates in nowadays: the anti-consumer practice of forcing customers to pay indefinite, exorbitant fees to still never be able to own the product they paid for, while also constantly being at the mercy of whatever internal company policy is forced upon them in the Terms of Service agreement the customer is required to accept. The frustration of reading that long-winded sentence pales in comparison to the soul-crushing anger from realizing that the future is heading to a point where corporations own everything, and the consumer pays for it. And if every corporation is pushing to automate every aspect of their organisation with AI, the machines will be our enslavers. Flux is generous enough to provide a free education edition with many of the advanced features of the pricier plans. This was great as it allowed for testing of the AI agent. As far as it has been tested, the agent is capable of doing everything Flux claims it can, but this is not saying much since the 50 free monthly credits included in the education version only got the agent to place one component in the designer. To put this issue into perspective, it costs \$4 per 100 credits, on top of the monthly fee required to use the program. This means it costs \$2 for each component of the PCB, not including routing, and most importantly, not including user/AI errors. This implies the cost of designing the PCB using Flux can infinitely skyrocket. See **Appendix B, B.1.2** to view the test of the agent.

There are many more issues with Flux, but the main focus of this section is on the efficacy of the AI agent. The AI agent appears to work really well. Sadly though, the current business practices of Flux cause the agent to fail. Flux does not appear to want to harm their future customer base, but a much better program would be something a customer can pay a one-time fee to own, and the agent can run and access the web solely using the customer's own hardware. Additionally, Flux could keep a free cloud-based version where customers pay for the AI credits in order to design PCB's on the go when they cannot access their main machine. A program like that could potentially dominate the eCAD market.

5.2 KAI FORD'S APPLICATION OF AI

5.2.1 Limitations, Pros, and Cons of AI Use - Kai

My utilization of GPT-5 is consistent with that of the virtual assistant concept that has become popular in recent years. I leverage the model for high-level research and as a way to parse through large amounts of data for points of interest. I will discuss the benefits first, followed by the limitations. The first and most tangible advantage provided by GPT-5 was efficiency. Prompting accelerated early drafting by enabling me to upload datasheets and ask the model in plain language, "where can I find the registers that control X system?". Additionally, GPT-5 is trained on a vast quantity of C code, making it a useful tool in adapting drivers for embedded software. While all of this information must be reviewed independently after citation by the LLM, these two capabilities combined save a lot of time when combing through datasheets and translating over register maps. In that same vein, GPT-5 has been useful in highlighting missed areas of consideration, as well as clarifying unfamiliar terminology. A major convenience has also been the ability to cite sources in IEEE format instantly, just by prompting a link to said

source. In the vein of citation, it is also valuable to ask GPT-5 to cite where it got technical information from. That way, you can reference the work that it's pulling its assumptions from and check for accuracy before utilizing figures or values that it provides.

Despite these strengths, several significant drawbacks must be acknowledged. The most serious is the issue of factual accuracy. GPT-5 generates language based on learned patterns rather than verified knowledge. It can confidently provide information that is technically incorrect, outdated, or inconsistent with actual data. For instance, the model had responded to one of my prompts about modulation schemes for the TiCC1101 by saying that a Part 15.247 compliant setup would be “highly unusual” for my chip. This was not true, as I was able to find documentation specifically supplied by Ti for how to configure the module so that it utilizes digital modulation in compliance with Part 15.247. If such text is copied directly into a report without verification, it may propagate errors and compromise our progress. For this reason, it is still very important to verify any claim, equation, or numerical value produced by the model. And finally, it is important to note that GPT-5 also has significant trouble with contextualization. While the model can understand instructions and generate coherent paragraphs, it does not maintain any real depth of project-specific knowledge. It demonstrates a notable lack of competency when covering topics outside of its typical training data, such as describing the subtleties of experimental conditions, component tolerances, or trade-offs. Sometimes, this causes the model to generalize or omit critical details.

Taking all of these factors together, it is best to utilize ChatGPT and other LLMs like it to perform broad, cursory research and assist with highly standardized, repetitive tasks like forming citations. These models can point you in the right direction with fair accuracy and save enormous amounts of time, but they should be very cautiously leveraged for any highly technical information.

5.1.2 Examples of AI Use - Kai

- Go in to detail about the pros and cons of using these types of modules in the context of a low-profile pulse oximeter that is broadcasting its readings to an external base station... (type of part here)
- IEEE cite this: (link)
- Where can I find the registers in this datasheet that drive the [particular system] system? (Attach datasheet)
- Are there any standards that would apply to my projects as described?
- Compare the advantages and limitations of using [component/module name] for short-ranged data transfer at 915 MHz in terms of power efficiency, range, and integration complexity.
- Explain how [specific pin or subsystem] functions within the [part name] architecture and how it affects RF performance in a compact design.
- Cite the relevant clause from [standard name or document] that corroborates your previous statement.
- Locate and describe where in the attached standard applies to my project. (Attach standard)

- Assess the suitability of [transceiver name] for [insert modulation scheme].
- What FCC and IEEE standards govern unlicensed RF data transmission for medical or health monitoring devices in the ISM band?
- In the context of a wearable transmitter, analyze how human-body proximity would alter antenna impedance and radiation efficiency for [antenna type].
- Summarize how [insert MCU] handles startup initialization, focusing on how the SPI interface programs key RF control registers.
- Discuss the implications of the specified output matching network in [application note] with respect to harmonic suppression and conducted emissions.
- Determine whether [transceiver IC] includes an internal LNA/PA or requires an external front-end amplifier for optimal operation.
- Explain what PCB layout strategies minimize parasitic coupling between circuit elements in the following circuit. (Attach schematic)
- List potential causes of communication failure between [insert MCU] and the CC1101 during SPI initialization, referencing timing or logic-level considerations.
- At this git repo, somebody has developed drivers for [insert hardware] that performs [function]. Translate the register map over utilizing this datasheet [link] for my microcontroller.

5.3 TYLER TAKIMOTO'S APPLICATION OF AI

5.3.1 Limitations, Pros, and Cons of AI Use - Tyler

The limitations of AI tools have been showing themselves as they've been utilized more often. One of the most apparent is the generation of ideas. There was a personal experience recently, where I repeatedly asked LLMs to create some ideas for a specific field of interest and it kept regurgitating the same few ideas over-and-over. This limitation comes down to how the models are created, since they cannot introduce new ideas. Large language models have to train off of pre-existing data that lead their thinking process and how to respond to certain questions. Since the models only know what has been given to them, being prompted to generate something entirely new seems to be out of the picture. One way to think about this is the following: Could an AI model know the exact solution to traveling as fast as light? There could be plenty of theories out there that the AI knows and can talk about, but creating something never done before would be out of the picture due to needing proven and existing data.

Benefits of using AI are vast and constantly being expanded upon. One of the main ideas is providing easy-to-obtain knowledge. The digital era has made information more accessible for the greater public, but now there is a resource that can also answer just about any question with great speed. Before, you'd have to either go to specific people or areas online to get good answers but now it's all in one spot.

Unfortunately, large language models have a ton of downsides when using them. For one, it can eliminate critical thinking and lead to brute forcing solutions. If you don't understand a homework assignment and have AI do it, that removes the learning aspect. It is understandable to have AI assist in homework completion, but doing the work for you is defeating the purpose of having assignments.

5.1.2 Examples of AI Use - Tyler

Gathering research papers about specific topics was a big use of AI. Instead of sifting through several papers about a general topic in hopes of finding something that fit, prompting a large language model to find the papers itself was a great assistance. By doing this, it was able to provide tailored research that saved plenty of time. Additionally, asking the model questions relating to specific papers was great in enhancing the reading material. Occasionally, there would be some topics that weren't very clear but AI would be able to decipher and clearly talk about the main ideas. This is most prevalent in newer models as they can go through websites and articles to read them and provide great explanations.

Another example is creating an outline from which to start writing. Sometimes starting a paper or topic is difficult, and reading how someone/something else approaches the beginning is the inspiration needed to get started on your own. Given the large amount of content that is necessary for this paper, it is incredibly helpful to have a tool that gives a starting boost where immediate progress can be made.

5.4 BENJAMIN WILL'S APPLICATION OF AI

5.4.1 Limitations, Pros, and Cons of AI Use - Benjamin

AI should serve as a tool and an assistant to the researcher or designer, rather than a replacement. With the somewhat recent ability for AI to browse the internet, asking AI to find research papers and other sources significantly hastens the research process. Instead of classically finding them one by one, AI can give an entire list. In this case, speed is a large benefit of using AI. Another benefit of AI can be on-demand explanations. Instead of waiting for someone to explain a concept or struggling with a vague idea, I can ask AI what something means. I can ask what a technical phrase means, or how a certain circuit is used in a design, without needing to spend time contacting someone. This is also tied to the speed benefit, as AI is easily accessible.

The limitations of AI is that it is not all-knowing, and it just regurgitates what it finds on the internet. Asking for research papers is fine because I would read the sources it provides me with. But with other information, it might not provide me with a source and could be factually wrong. The internet is not a 100% truthful place with 100% facts. The AI will push forward the top results, which sometimes are not the best results. Ideally, people should not completely trust what the AI gives them and do their own research alongside the AI. But the temptation of getting a job done quickly and moving on can be too strong. If I fall victim to this, it will harm my senior design paper by using false information and possibly lead to a faulty design in our project.

5.1.2 Examples of AI Use - Benjamin

To speed up the research phase, I have asked AI to provide me with sources that compare and contrast the features of the different types of batteries. Just a few moments later, it gave me a list. Within seconds, I had a small list of relevant sources about different

batteries and how they compare to others. I could have easily searched these up myself, but AI made it a whole lot quicker.

Instead of wasting my time thinking of a decent transitional sentence in one of my paragraphs, I asked AI to create one for me. It provided a sufficient sentence that connected my previous thoughts to the next. Although the purpose of this paper is to articulate our thought process for our project, the important part is the project itself. So this use of AI helped me move on from the mundane task of thinking of a good sentence to a more beneficial task, like researching other batteries.

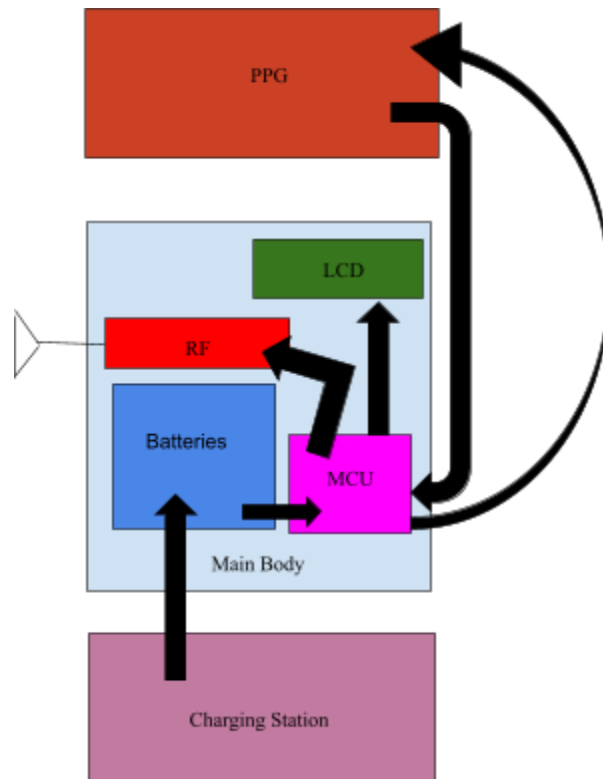
Another use of AI is that I asked it to tell me which standards our switch-mode power supply may be subjected to in the United States. One quick question gave me back a list of standards and some definitions. It mentioned the FCC Part 15 and the 10 CFR Part 430. I took a look into these, and they were, in fact, required by law. Trying to search for “SMPS regulations” would probably have brought me to the same results; however, it would most likely have taken much longer. But one caveat to this is that it only listed required standards. Through more personal research, I came upon other voluntary standards like the IEC 61000-4, which the AI failed to mention. So this is an example of both a beneficial and harmful use in one. I was able to quickly find a few standards, but if I had stopped there, I would not have known about any other standards not mentioned.

6. HARDWARE DESIGN

6.1 HARDWARE DESIGN OVERVIEW

This section will go into the design of all our hardware components. We will be using our in-person experience and our research knowledge to build the device as we intend to. There are multiple sections to this, each to break down the specific areas we are working on. The PPG sensor sends the light signals that will be read and sent to the MCU, our MCU displays the results to the LCD, the RF module will use radio signals to send our data to a base station, and the power system will make sure our device can receive power.

6.2 OVERALL SYSTEM BLOCK DIAGRAM

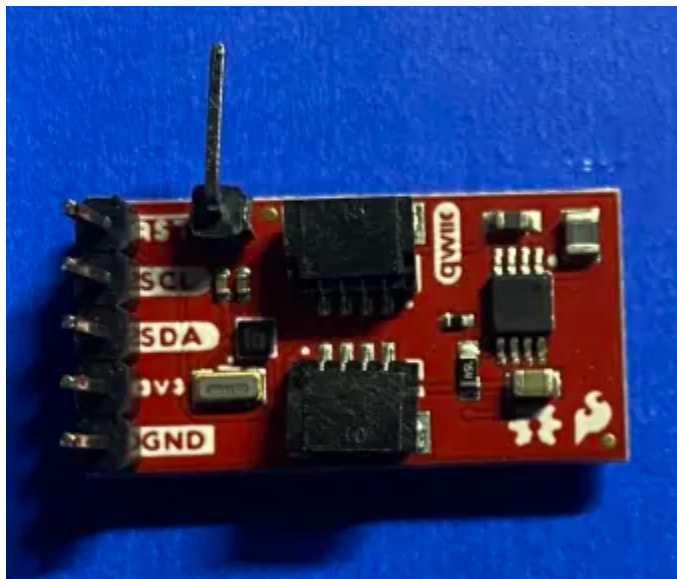
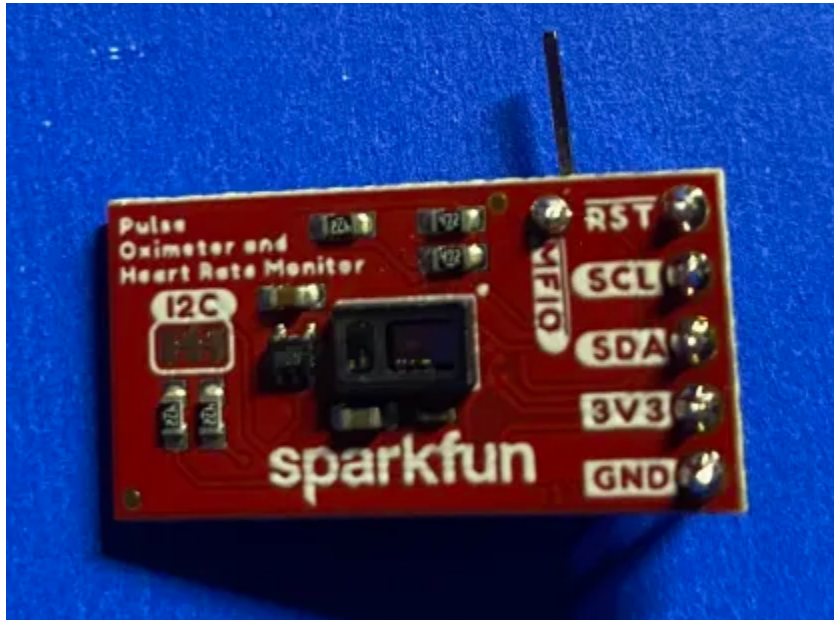


6.3 HARDWARE SUBSYSTEM DESIGN

6.3.1 PPG Sensor Subsystem

Due to the technical challenge soldering the MAX30101 onto a PCB would pose, the project was approved to utilize a pre-built development board for the sensor. The development board chosen was the SparkFun Pulse Oximeter and Heart Rate Sensor - MAX30101 & MAX32664 (Qwiic). The benefit of using this board is that it contains the MAX32664 chip which handles all of the complex digital signal processing. SparkFun also provides free public domain code to get the sensor board to function. The board was slightly modified by soldering header pins to it to make it easier to prototype with and

mount to its holder. How the PPG board mounts to the holder is discussed in section 8.2 of this report.



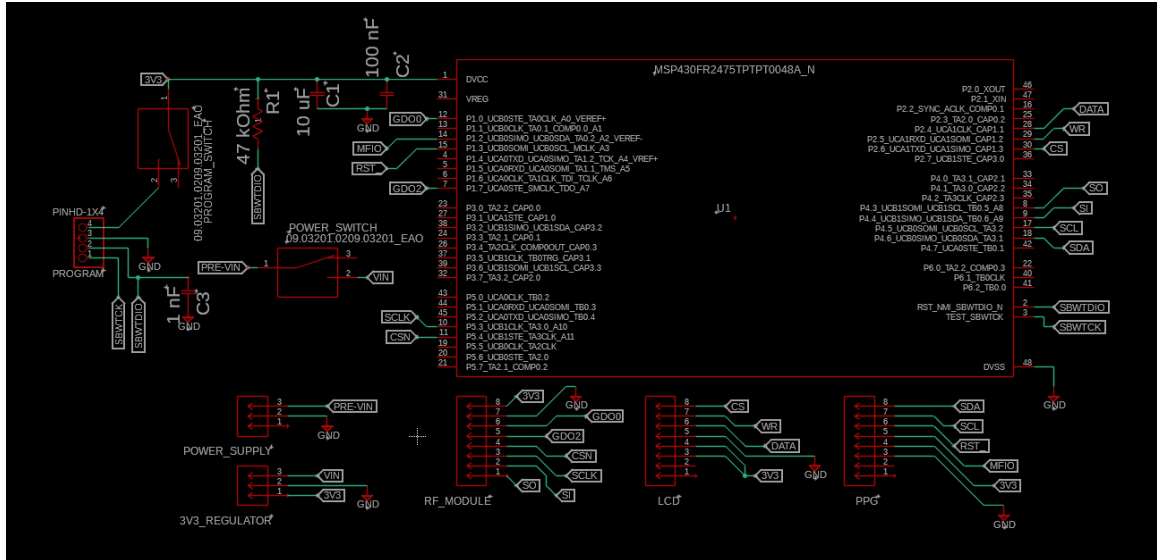
The project was also donated an SpO₂ clip, presumably the HC989903166531 Adult SpO₂ Clip MR Patient Care. This clip is designed to work with specialized medical equipment, and more specifically, a transmissive style PPG. It is mainly plastic with a silicon finger rest, a metal spring in the hinge, and lenses in the holes on both sides of the clip. These holes will be hereafter referred to as lens channels. Despite not being made for the application this project will use it in, the clip is still useful as it will provide a comfortable place to take finger PPG measurements in, limit noise from motion artifacts, limit noise from ambient light, and prevent errors from differences in finger perfusion caused by pressing too hard or too soft on the PPG sensor.





6.3.2 MCU Subsystem

The MCU subsystem is the main hub where all peripherals integrate. The MCU subsystem not only contains the MCU, but it also includes the 3V3 bus. Essentially, the MCU Subsystem is the central hub of the device where power and signals are shared to the required devices. A power switch controls whether the device is on or off. A header pin row allows the MCU programmed with jumper wires. A separate programming switch is needed to handle programming while on battery power, or while being powered by a dev board. All the switch does is toggle between the battery line or the external power source line.



6.3.3 Display Subsystem

For the display, we have four wires that we need to worry about. The display we currently plan on using requires 5V to use. Additionally, we need to connect the display to common ground. After that, the device uses I2C communication, so two wires for SDA and SCL are connected directly to the MCU. Since we have 6 digits to work with, we plan on splitting the numbers halfway for the heart rate and oxygenation percentage respectively.

6.3.4 Radio Transceiver Subsystem

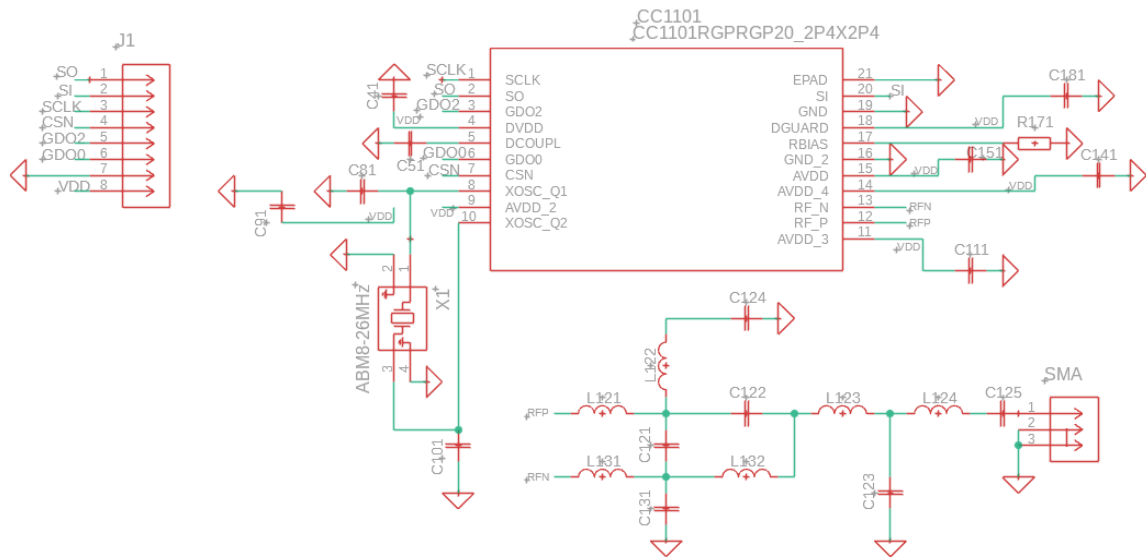
6.3.4.1 Transceiver Description

We must carefully design a circuit that effectively integrates the Ti CC1101 into our project. To do this, let's first dive into the purpose of all relevant pins on the module. Some pins are allocated to provide and manage the input voltage to the transceiver. This includes the DVDD pin (digital VDD), which may be operated between 1.8-3.6V. We will drive this pin with 3.3V from our regulator. We will also drive the analog voltage pins AVDD with 3.3V. There is also the DCOUPL pin: the output of the module's internal voltage regulator, which Ti explicitly says to connect to a 0.1uF capacitor in series to ground. DGUARD is a guard bias pin that serves to ensure separation between the analog world of the RF circuitry and the digital world of the device's communication. Even though both worlds share a silicon substrate on the module, a guard ring is implemented around sensitive analog components, which is a heavily doped area that "guards" these components from digital transients. DGUARD is also supplied with 3.3V. To avoid parasitic effects, decoupling capacitors are implemented at all voltage supply pins across the Ti CC1101 to provide a low-impedance path to ground for high frequency noise. These capacitors have a reactance that decreases as RF frequencies are approached. At DC and low frequencies, the capacitor has very little effect, while for high frequency transients, it acts as a short to ground. Traces in the PCB also add a significant amount of parasitic impedance, which is undesirable. It is for this reason that keeping the

decoupling capacitors within 2mm of the Ti CC1101 power pins is preferable [79]. That being said, as is the case for all PCB designs on this prototype, we aim to keep components reasonably spaced apart whenever possible and to use components that are large enough to be easily visible and solderable given our laboratory constraints. Many pins will also be hooked up to our MCU directly so that the transceiver can be driven via SPI communication. This includes SCLK (the serial clock), SI (MOSI), SO (MISO), CSn (Chip Select, Active Low), and the status output pins GDO0/GDO2. The XOSC_Q1 and XOSC_Q2 pins connect to the terminals of the 26MHz crystal inside of the module, which acts as an internal timekeeper for the transceiver. Then, we have the pins that serve the critical function of propagating energy towards the RF front-end (RFE). A differential (common-mode noise mitigated) voltage signal is driven across RF_P (the positive terminal) and RF_N (the negative terminal). RBIAS connects to a biasing resistor of $56k\ \Omega \pm 1\%$ impedance by Ti's recommendation. This resistor is utilized internally to set a bias current that drives the low-noise amplifier (LNA) and other important RF circuitry, so it is important to follow the manufacturer's instructions closely here. Similarly to with the decoupling capacitors, we want to maintain a short distance between the RBIAS pin and our bias resistor, as well as a short distance from the bias resistor to ground to avoid parasitic results from extended traces. At the RF energy differential output, we must design a matching network to convert the complex impedance viewed at the port ($86.5 + j43\ \Omega$) to $50\ \Omega$ at the SMA. This is done using the balun design described by Texas Instruments for this module [80]. The balun design then connects to an optional filter before reaching an SMA F termination.

As for reception, a CC1101 evaluation board may be utilized in connection with a PC through interfacing with the SmartRF Studio software provided by Texas Instruments.

6.3.4.2 Transceiver Schematic



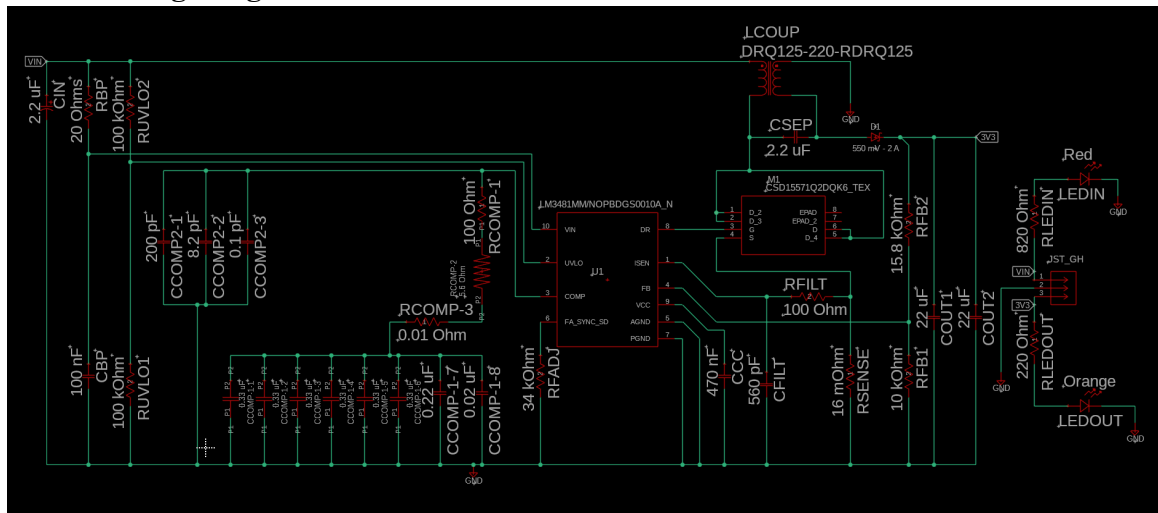
6.3.6 Voltage Regulator Subsystem

6.3.6.1 Voltage Regulator Description

All subsystems other than the power supply system and display can or need to run off of a 3.3 V supply. However, the nominal supply voltage from the power supply can be 3.7 V when operated purely on battery or 5 V when operated while charging from wall power. To provide a generous range of functionality for the PPG device, its regulator was designed using WEBENCH® to continue supplying 3.3 V output from a 3 V to 6 V input. The entire PPG device should never draw more than 200 mA, yet a generous maximum current output limit of the regulator was chosen to be 1 A.

These generous operating limits meant the regulator had to be a switching regulator with either a Buck Boost, SEPIC, or Flyback topology. The simplest design WEBENCH® offered was a SEPIC topology utilizing the LM3481 controller. Some modifications were made to the WEBENCH® schematic due to component availability. Also, LED indicators were added for debugging purposes. Despite being the simplest circuit offered, it is still very complex. If this regulator design ends up being too troublesome, the operating limits of the regulator will be tightened and a simpler circuit will be chosen.

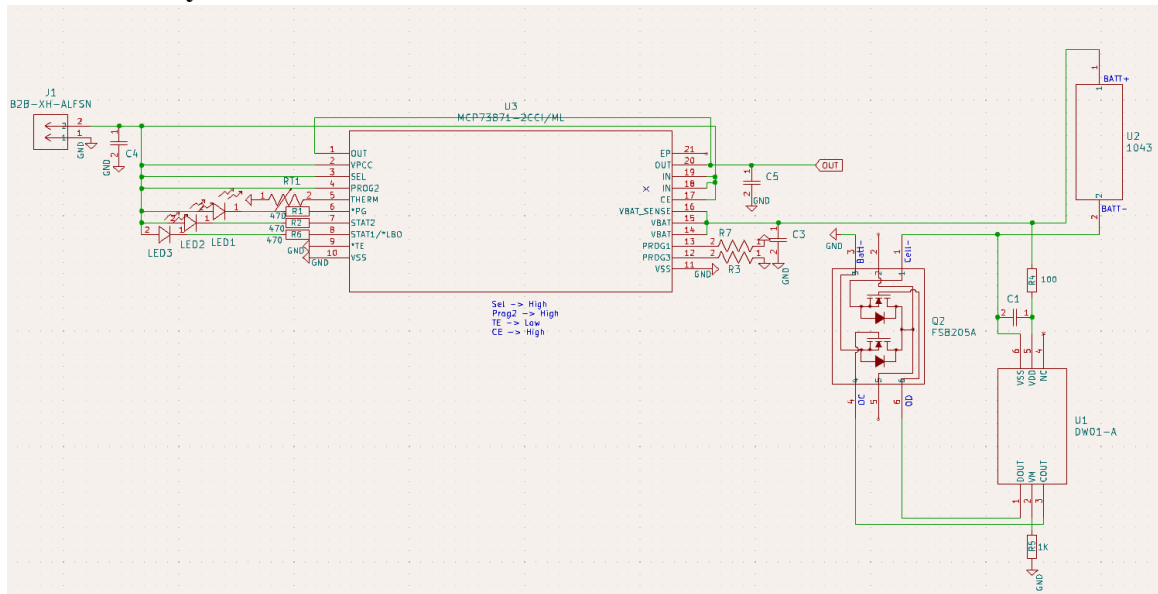
6.3.6.2 Voltage Regulator Schematic



6.3.7 Battery Subsystem

In the battery subsystem, the design centers around the dedicated lithium-ion battery charging IC (MCP73871) and the low-side protection IC (DW01). This circuit requires accurate component placement and connection as to not accidentally short the battery and have it burst into flames. Even if it does not catch on fire, the cell becomes irreversibly damaged and is unsafe to use afterward. This is also why a protection IC with a low-side dual NMOS chip is used to help protect the battery in normal operation.

6.3.7.1 Battery Circuit Schematic

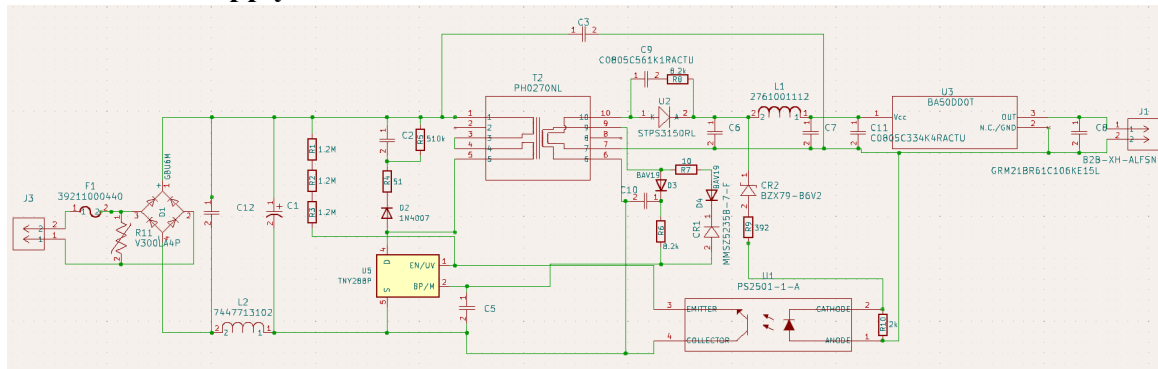


6.3.8 Power Supply Subsystem

To have regulated DC output from the AC line, we have chosen the flyback topology, and the TNY288 as our flyback power switch to achieve this. This switch-mode power supply involves high voltage AC power and converting it to low voltage DC power. We must use both high and low-voltage components: high-voltage parts to safely handle AC wall power on the primary side, and low-voltage parts that won't cost as much on the secondary side.

The output voltage of the flyback converter section of the power supply is configured by a zener diode connected to the output rectifying diode, filter, and subsequently connected to the optocoupler. The specific breakdown voltage of the zener diode dictates the output voltage the power supply will be configured to. Since we are using a linear regulator, this voltage must be above the dropout voltage of the regulator plus its output voltage. For our selection, this gives us a minimum zener output voltage of 5.7V. However, we opted for a little bit more headroom and selected a 6.8V zener diode. Switch-mode power supplies do not necessary need such a regulator as the voltage reference and feedback circuit are adequate enough to provide a stable output voltage. However, the use of a linear regulator provides extra ripple rejection which reduces the noise generated by the high-frequency switching. It simultaneously increases the load regulation capability of the entire power supply, further increasing the reliability of the voltage output on various load conditions.

6.3.8.1 Power Supply Schematic



7. SOFTWARE DESIGN

7.1 SOFTWARE DESIGN OVERVIEW

The software is the final component of our system, responsible for transforming the raw sensor data into readable heart rate and SpO2 data. To be consistent with our overall project goals, the software will primarily focus on performance and low power consumption. This goal is accomplished through the usage of bare-metal programming with the C language. No overhead from an operating system will slow down the processing and C allows full control over memory management to maximize performance. Furthermore, we will be taking full advantage of the MSP430FR2475's low power modes with interrupts and timers. This way, we avoid unnecessary MCU clock spins and can focus on the processes that must happen when needed. Most of the logic for this system occurs in a continuous loop, where sensor data is constantly being read and analyzed by the program to return our critical data. We will also account for moments when finger data isn't being scanned to avoid over-consumption of power.

7.2 OVERALL SYSTEM BLOCK DIAGRAM

A high-level diagram was previously shown how the system would work, but now that we've gotten more information about how the software needs to be structured to get our data, we can dive into the specifics of design. The MCU will be controlling everything, from when LED signals are sent to low power mode.

Our system will by default be in an inactive state, where no unnecessary calculations occur and we draw as minimal power as possible. Once we've detected a finger being inserted in our device, we can then go into an active mode. At this point, we begin the main loop of sending LED signals and reading the light levels. We'll take some time to read the data and ensure a quality result. If the user's finger leaves the system during data reading, we'll display the last read heart rate and oxygenation while starting a timer to turn off the system.

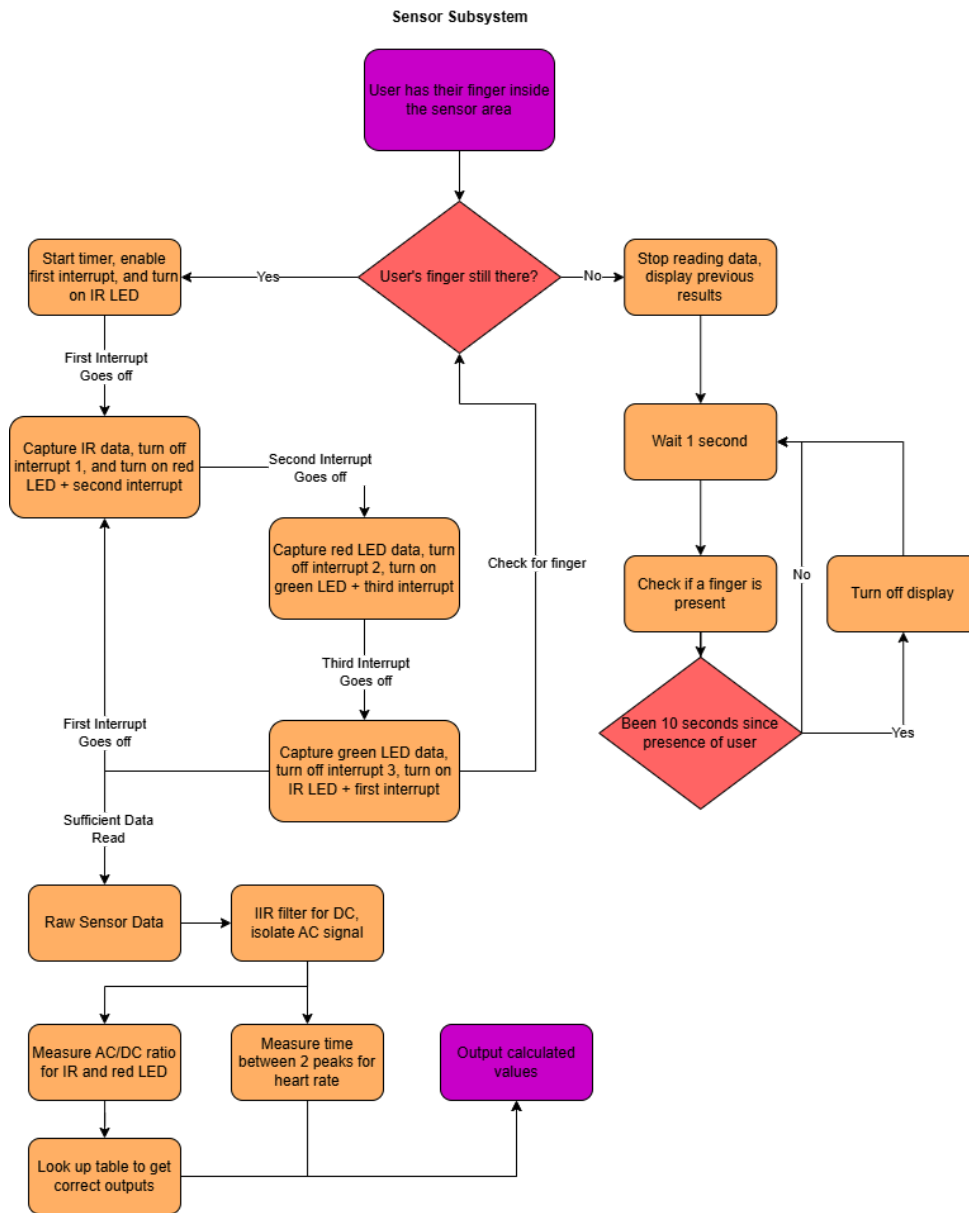
7.3 SOFTWARE SUBSYSTEM DESIGN

7.3.1 Sensor Data Subsystem

As our foundation has been built, we can discuss the real design of the software. Let's focus on the main goal, obtaining SpO2 levels and returning the oxygenation plus heart rate. To get our results, we read the current that is generated by the photo-diode as it reacts to received light [130]. As previously discussed, the current received is extremely small, so it will be amplified with "a low drift current" before being read [130]. At this point, we have two electrical measurements to read, the direct-current and alternating-current values. To get our currents, we can use a specific sequence given to us by [130], Texas Instruments, which uses one timer and three CCR interrupts when using a Dual Wavelength PPG Sensor. The interrupts swap which LED is currently active to capture different data. When we start the timer, we emit the IR LED. Once our first interrupt comes by we use an analog-digital converter (ADC) to capture the IR's light data. The first interrupt closes, and turns on the red LED. After some time the second

interrupt will occur, using the ADC to capture the red light information and turning off the red LED. After both lights have gone off and some time passes, the final interrupt for a Dual Wavelength PPG sensor passes and captures ambient light. Adapting this sequence to a Triple Wavelength sensor means that we add a step, most likely after the red LED, where we turn on the green light and read the current signal. Once that has been done, we'd then proceed to the ambient light capture that was specified previously. The current amplifier that was mentioned will be used after each light reading to make sure the software can read the small signals. Once we have this sequence down, we need to process the signals to decipher their meaning. Going back to the current signals given, we know that DC corresponds to non-pulsatile parts of the body. Since we care about the pulsatile components, we filter out the DC values so we can read our AC signal. To do this, a "low-pass IIR digital filter" is implemented [130]. An IIR filter is short for an infinite impulse response, which gets the difference of the previous output and the new input to create a new output value. With the result of this filtered DC signal, we use this as the base line for finding the absorption with AC. Once we can read our AC signal, we need to decipher it for heart rate and oxygenation. With our AC and DC we can measure the pulse and oxygenation as needed. First, the simplest is the pulse rate. This would simply be the time either between two peaks, or two onsets, of the green AC signal. For heart rate, we get the ratio of our red signal over the IR signal. This corresponds to an SpO2 reading that we can grab via a "look up table" to get a correct reading [130].

7.3.1.1 Sensor Data Subsystem Diagram

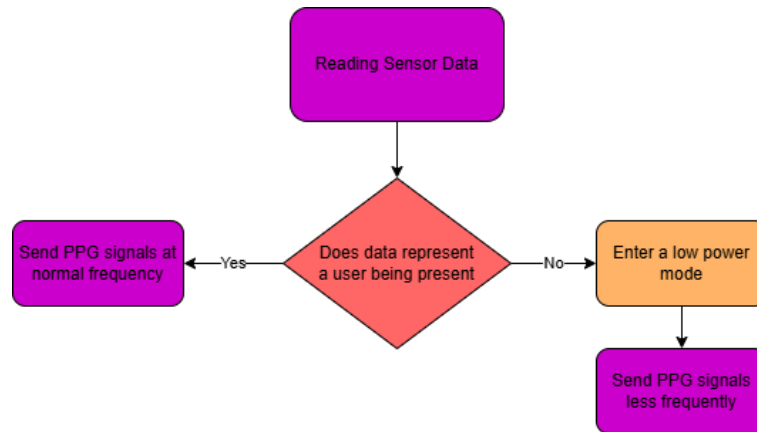


7.3.2 Power control Subsystem

Having an intricate system that controls when we go into different low power modes and turning off/on can lead to energy savings when no power is needed. One of the main ways we deal with this is detecting finger readings when the system is powered on.

When no clear finger data is present, we will enter a low power state where we very occasionally will send LED signals to the PPG sensor. The longer no finger is present, the longer the delay for checking a user's presence, eventually also turning the display off. This way, if a user accidentally leaves the system on it can preserve energy without being powered down. Of course, when the user eventually re-inserts a finger we re-enable all of the systems needed to monitor heart rate and oxygenation.

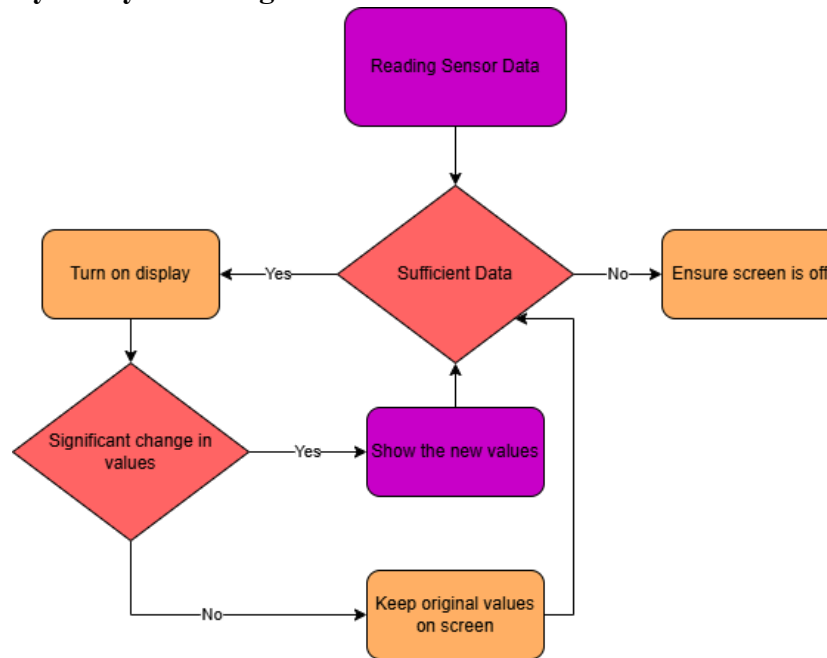
7.3.2.1 Power Subsystem Diagram



7.3.3 Display Subsystem

Delivering the data in a clear and readable format is integral to the user experience and understanding of the device. Since we are choosing a segmented display, various functions will be created that can create all 10 digits necessary to display. This way, the programmers gain easy access to setting the display values. Furthermore, the system will recognize when certain digits don't need to be on, such as a 2-digit number not using three digits to show the value. The MCU will control when the display will be updated with new information, making sure updates aren't too frequent as to prevent the user from understanding their measured values. Physical labels will be provided on the board to let the user know which section of the LCD corresponds to oxygenation or heart rate. Additionally, we can add extra information about what the numbers mean to give the user context to their values compared to what they should be.

7.3.3.1 Display Subsystem Diagram



7.3.4 RF Subsystem

7.3.4.1 - CC1101 Registers

The CC1101 natively supports digital modulation for packet transmission. The MCU will communicate to the CC1101 via SPI. The MCU formats pulse rate and blood oxygen saturation data into packets and streams it over the SPI bus to the CC1101, which handles modulation, framing, and transmission. The base station will ideally be implemented with another CC1101 configured in receive mode, which decodes the packet stream and forwards the recovered data to a higher-level processor or network interface. Since the receiver PCB design is not in the scope of our project, we will likely utilize a development board that integrates the CC1101 to easily verify the prototype's onboard transceiver. The transceiver front end is made up of a matching network, optional filtering of spurious emissions if the 169MHz carrier frequency is utilized, and a monopole antenna connected via SMA. Because the CC1101 supports programmable output power up to roughly 10dBm, and has the capability to maintain sensitivity as low as -110dBm, it will be incredibly feasible to make link in accordance with our requirements. The device's digital interface follows a straightforward SPI protocol (four wires: MOSI, MISO, SCLK, CSn) plus an optional GDO0/2 pair for packet-ready or sync interrupts. The MCU must be leveraged to set defaults for the following CC1101 registers at startup, placing the transceiver into IDLE, CALIBRATE, or TX/RX states as required. Power management is crucial in our use case, so it will be important to utilize the CC1101's SLEEP state where the crystal oscillator is disabled. This will allow us to drop consumption below 1µA while the device is not being actively utilized.

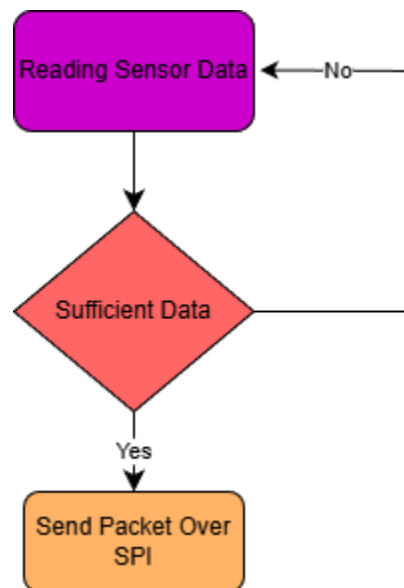
Texas Instruments provides default register templates through the SmartRF Studio software. These templates cover modulation format, frequency synthesis, data rate, deviation, packet handling, and calibration timing. Understanding which registers are

critical and what function they perform will allow us to adjust modulation parameters to satisfy both data transmission requirements and meet regulatory constraints. The `FREQ2`, `FREQ1` and `FREQ0` registers set `FREQ` and the carrier frequency of the message is established according to a mathematical relationship that incorporates the current channel [85].

We then select the modulation type through `MDMCFG2.MOD_FORMAT`, where the codes 00 = 2-FSK, 01 = GFSK, 10 = ASK/OOK, 11 = MSK. The data rate derives from `MDMCFG4.DRATE_E` and `MDMCFG3.DRATE_M`. If we intend to ensure 15.247 compliance, the 6dB bandwidth must exceed 500 kHz. Combinations such as 250kbps with $\pm 200\text{kHz}$ deviation or 500kbps with $\pm 125\text{kHz}$ deviation would satisfy this condition. Output power is adjusted through `PA_TABLE` entries. TI provides dBm levels for the following registers: (0xC0 $\approx$ 10dBm, 0x84 $\approx$ 0dBm, 0x50 $\approx$ -6 dBm) [85]. For operation under Part 15.247 digital-modulation limits, the conducted power must not exceed 30dBm, but with our low gain monopole antenna, this will not be problematic.

A C library under an MIT license was utilized to derive the driver format for the CC1101 [87]. We adapted the code for our particular microcontroller.

7.3.4.2 - RF Transceiver Subsystem Diagram



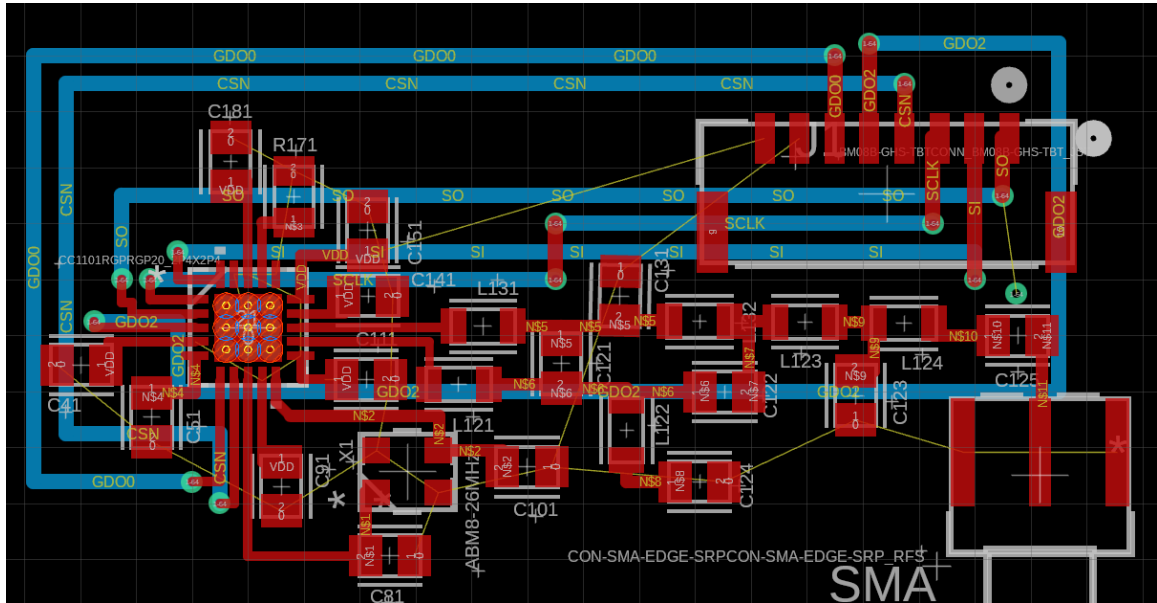
8. SYSTEM FABRICATION/PROTOTYPE

8.1 PCB LAYOUT

8.1.1 - RF Transceiver Subsystem

8.1.1.2 Transceiver PCB Layout

The CC1101 will be integrated with decoupling capacitors and a matching network on a PCB. The PCB will have a set of headers for 3.3V and SPI communication with the MCU as pictured below.

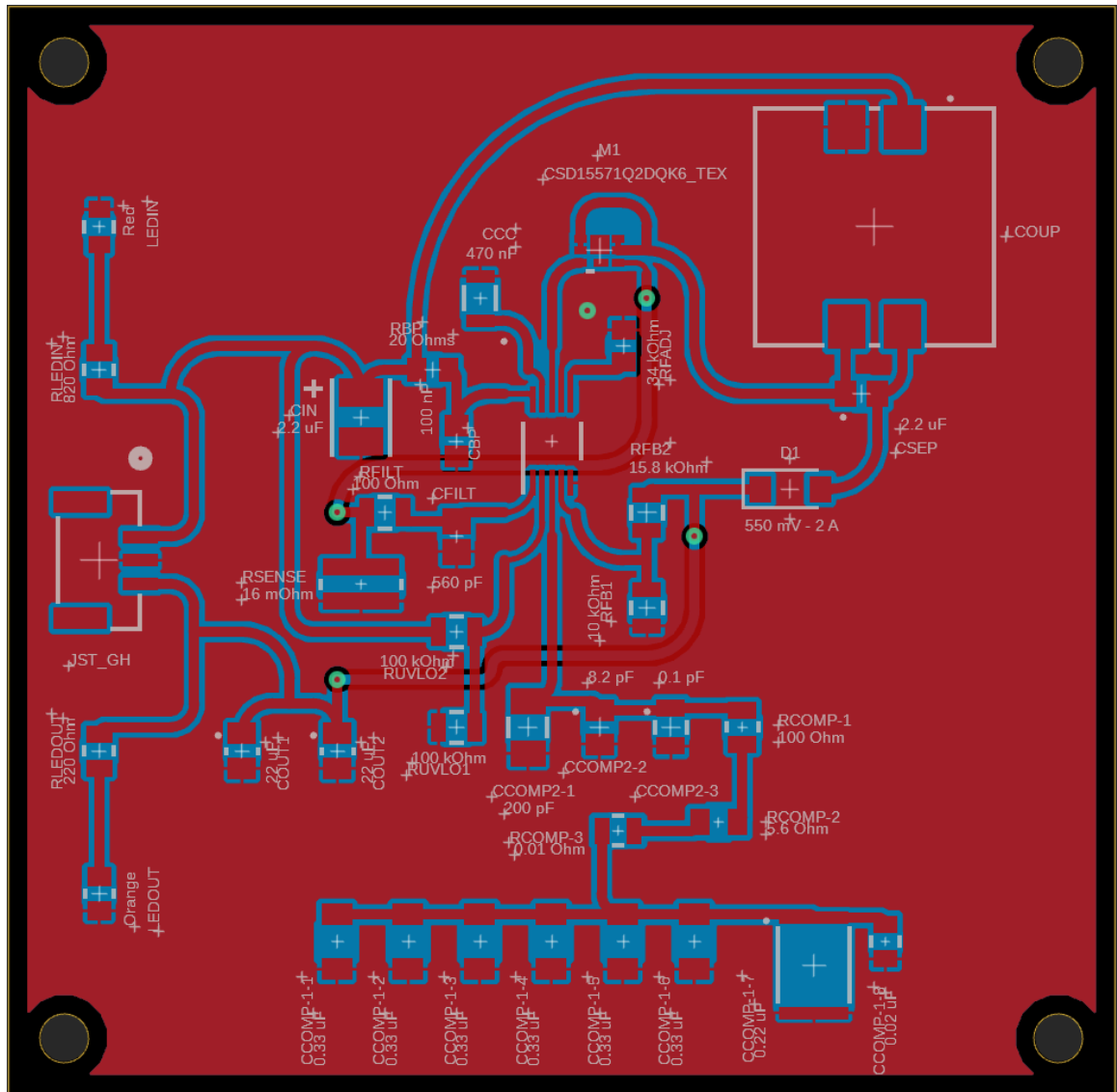


Note that grounding still needs to be established in the above PCB design.

8.1.2 Voltage Regulator Subsystem

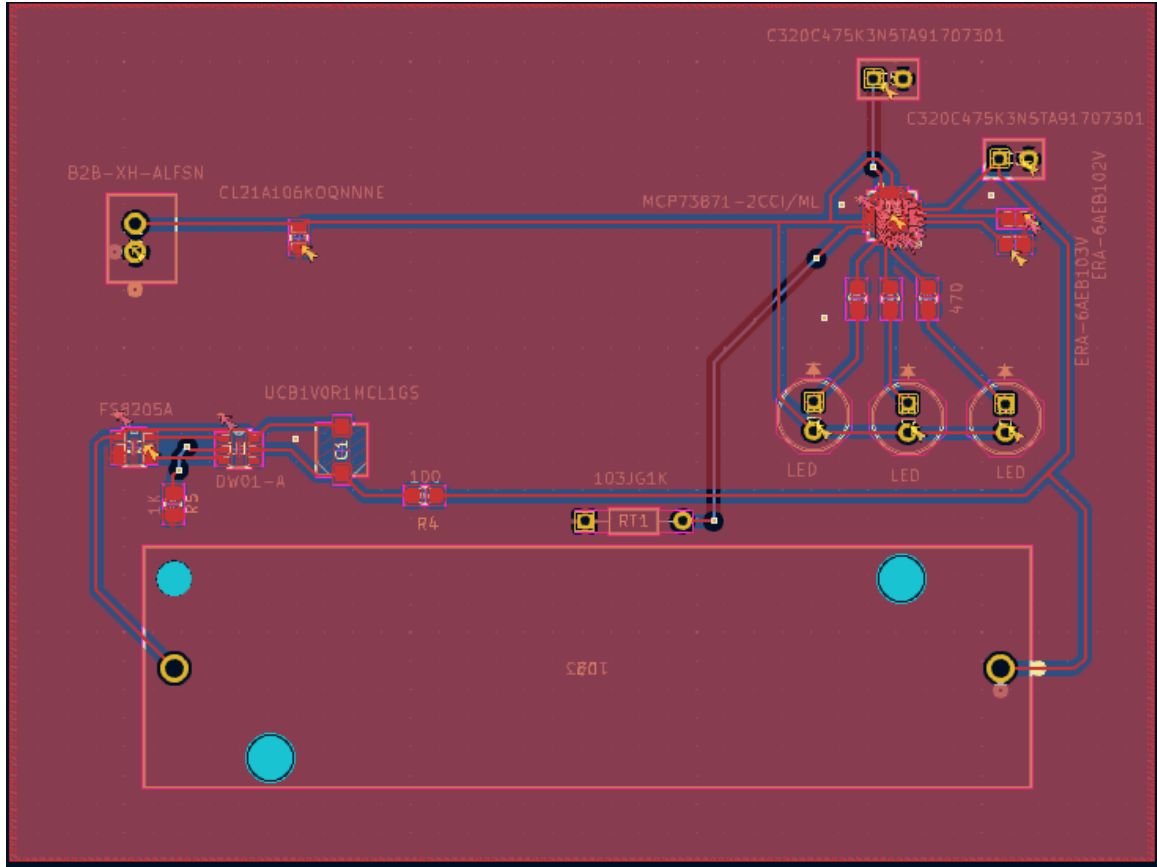
8.1.2.1 Voltage Regulator PCB Layout

Front:



The battery charging subsystem is a standard PCB with two separate ICs. For both of these ICs, coupling capacitors and resistors should be placed as close as possible to reduce parasitics. This board benefits from the ground plane technique, which is a large, continuous copper layer that acts as the circuit's reference ground. Not only does it make connecting ground nodes of components easier, it helps reduce noise and prevents ground loops in the circuit.

A feature of the charging IC is that it has a THERM pin that can be connected to an external NTC thermistor to detect the temperature of the battery, and terminate charge if it becomes too hot. In this case, the NTC thermistor must be placed close to the battery, and possibly even raised (via through-hole leads) to get as close as possible.



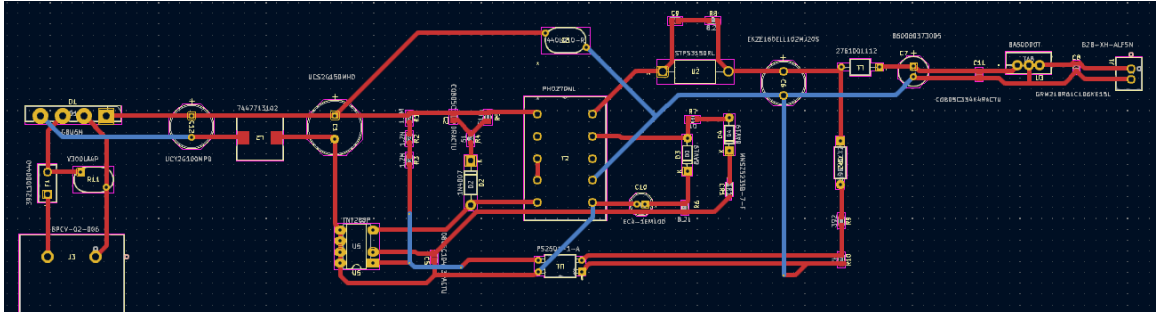
8.1.4 Power Supply Subsystem

The PCB layout of the switch-mode power supply must follow strict guidelines to successfully dissipate heat, isolate the high-voltage and low-voltage regions, and achieve minimal EMI. Further research needs to be done to adequately meet all of these goals.

The main heat generation of this pcb will come from the TNY288 power switch. This IC has four source pins that are internally tied to the lead frame to serve as the primary path for heat dissipation. That is why it is recommended to use a copper area underneath the IC to act as both a ground node and heat sink. The second most heat generating part is the output rectifying diode. It is recommended to have the cathode by touching the pcb with the anode pointing up in the air. This is so that the cathode of the diode has a large PCB area to dissipate heat into.

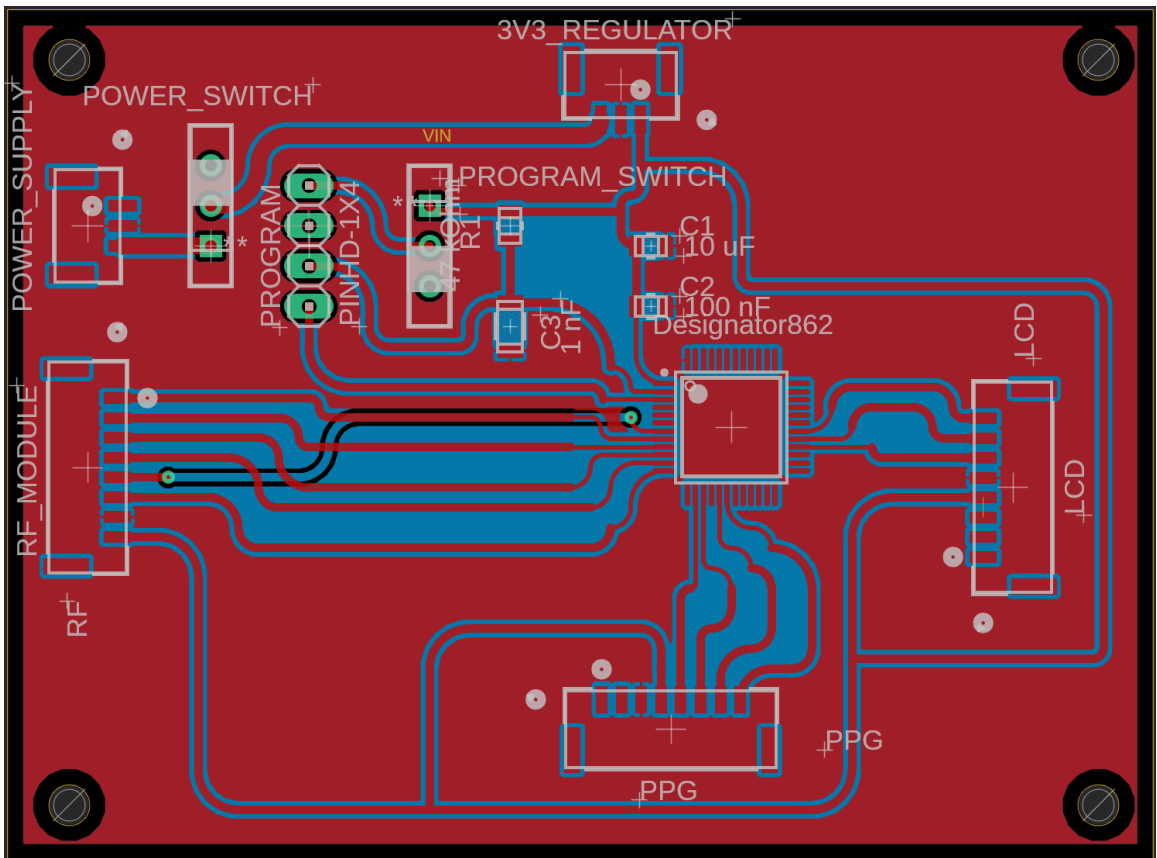
For isolation, there must be no electrical connection between the high-voltage and low-voltage side, and each side should be distinctly separate (future rendition will show separation clearly). The only components that do bridge these sides are the transformer, optocoupler, and a Y-capacitor. The transformer and optocoupler are required for the circuit to function correctly, while the Y-capacitor serves to return noise to the source and reduce EMI.

Apart from the Y-capacitor itself, the placement of it also helps reduce EMI. It is recommended to route the capacitor directly to the second input capacitor positive pin, and the other to the RTN pin of the secondary side. Another recommendation is the place the BP/SOURCE capacitor as close as possible to the TNY288. These recommendations will be implemented on our design in a future rendition.

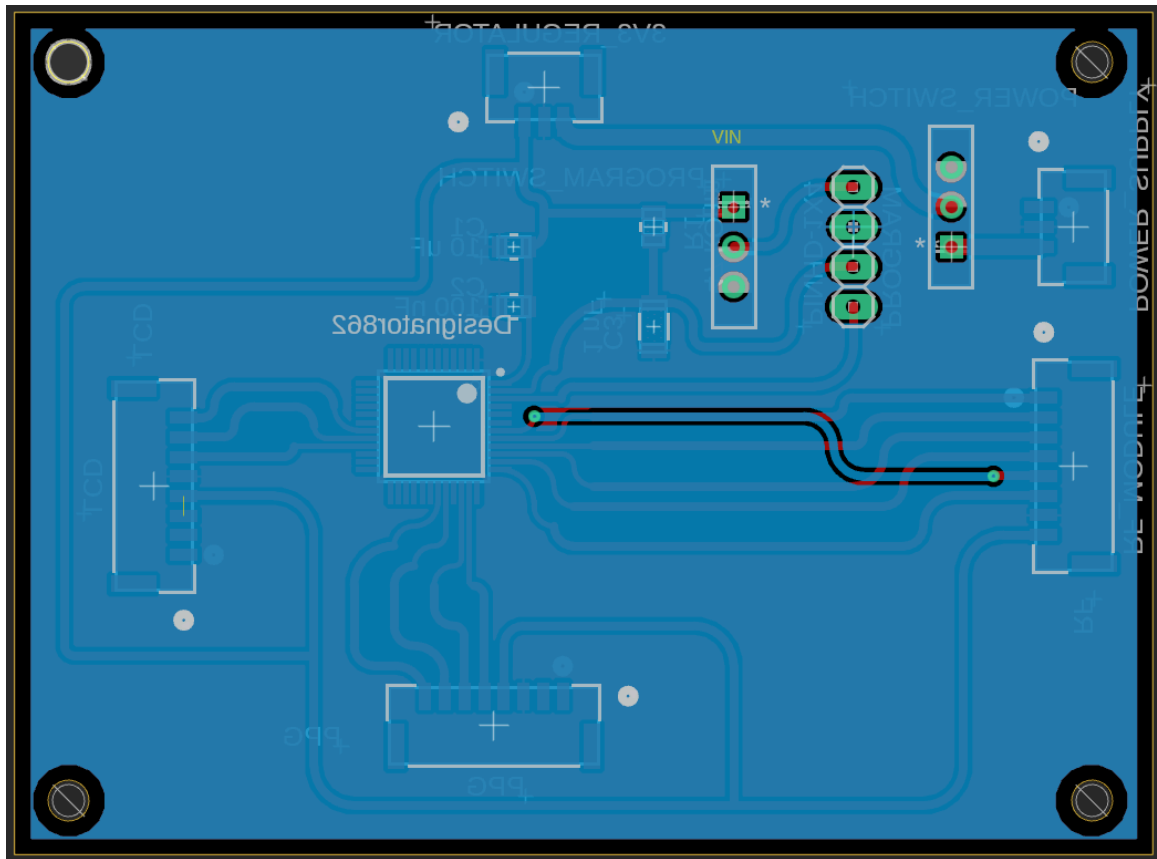


8.1.5 MCU Subsystem

Front:



Back:



8.2 CAD

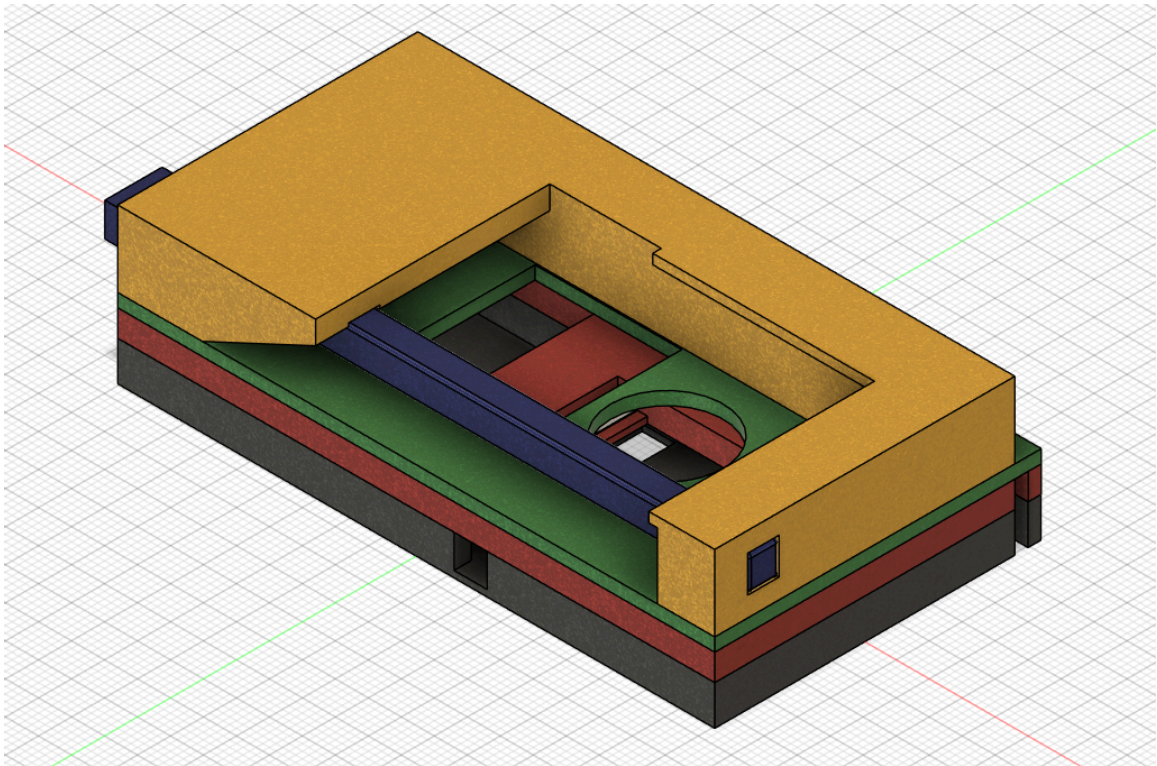
The three major structural parts of the overall system are the PPG Holder, the Main Device Body, and the Charging Station. The PPG Holder contains the most important subsystem, the PPG, and it allows for secure attachment to the finger while also reducing sources of noise. The Main Device Body houses the MCU, RF module, the batteries, charging circuit, and the 3V3 regulator. The Main Device Body will have to be sizable to account for all the necessary electronics as high density PCBs are not within the current capabilities of the members of this project and the equipment available to them. So, the PPG Holder was designed to be detachable from the Main Device Body to promote greater flexibility in positioning of the PPG to make it easier to utilize the device. For example, the Main Device Body can be set down on a table and the user can remove the much smaller PPG Holder and attach it to their finger so they do not need more than two hands to operate the device while taking measurements. The Charging Station holds the AC to DC power supply board. The user can recharge their PPG device by simply placing the correct end of it in the top of the station. Additionally, the Charging Station provides a stable footing if the user desires to use the PPG device while charging, allowing the user to create a static station to take measurements from instead of performing them mobilely.

Every part was designed to be 3D printed for cost and ease of design adjustment. All parts and board mounts of the device utilize socket head M2.5 bolts. This is so the device can be easily assembled and disassembled, and so that the end user does not damage the

bolts while doing so. The use of heat-set inserts makes the use of standard bolts possible by providing metal threads for the bolt to grip on to without having to worry about layer separation in the 3D printed parts.

8.2.1 PPG Holder

As mentioned before, the PPG Holder's objective is to securely hold the PPG and eliminate sources of noise in measurements. The PPG Holder is an assembly comprised of six parts, but is best described in four sections: the Finger Clip Adapter, the Finger Clip Spacer, the PPG Dev Board Holder, and the Backing Plate. Four bolts hold the parts together; the bolt holes are hidden when viewed from the top. Additionally, the PPG Holder has two small vertical rails on the back side (see the right corner of the holder in the image) and at each corner of the holder. These rails allow the holder to be easily removed and replaced from the Main Device Body.

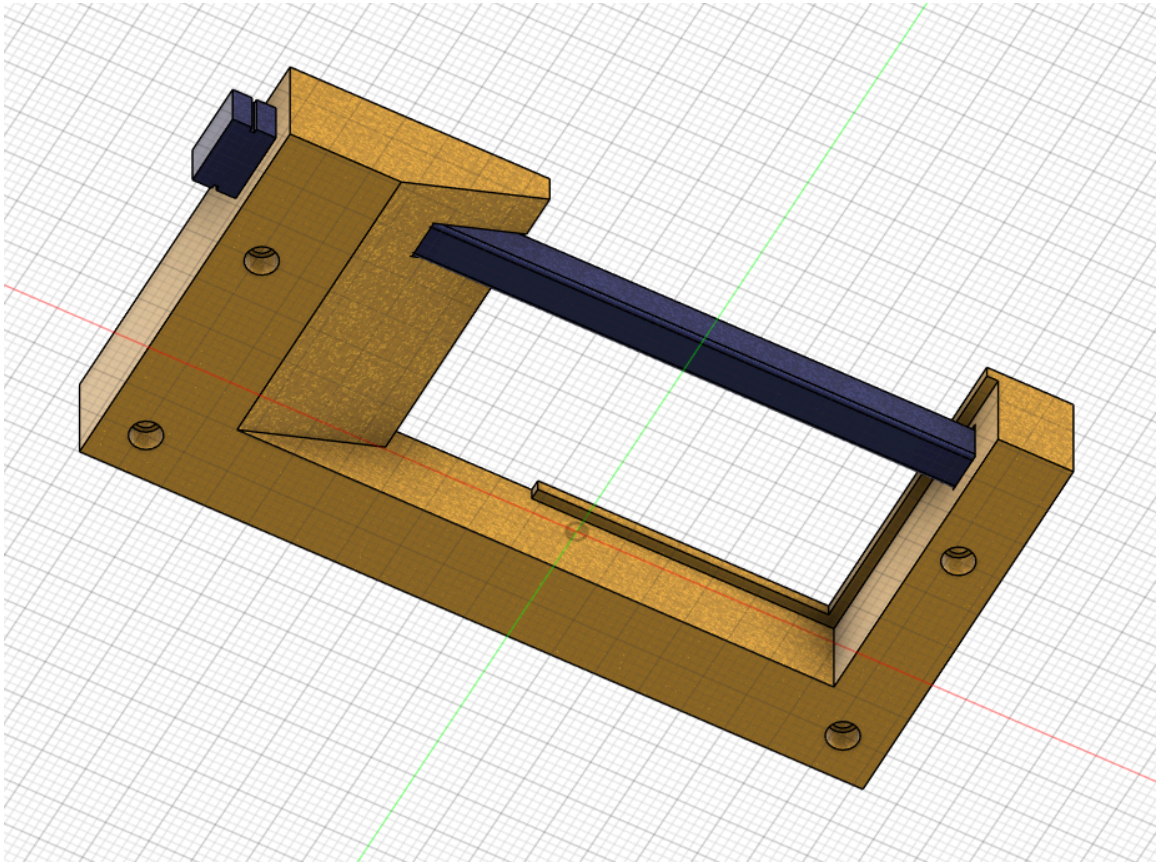
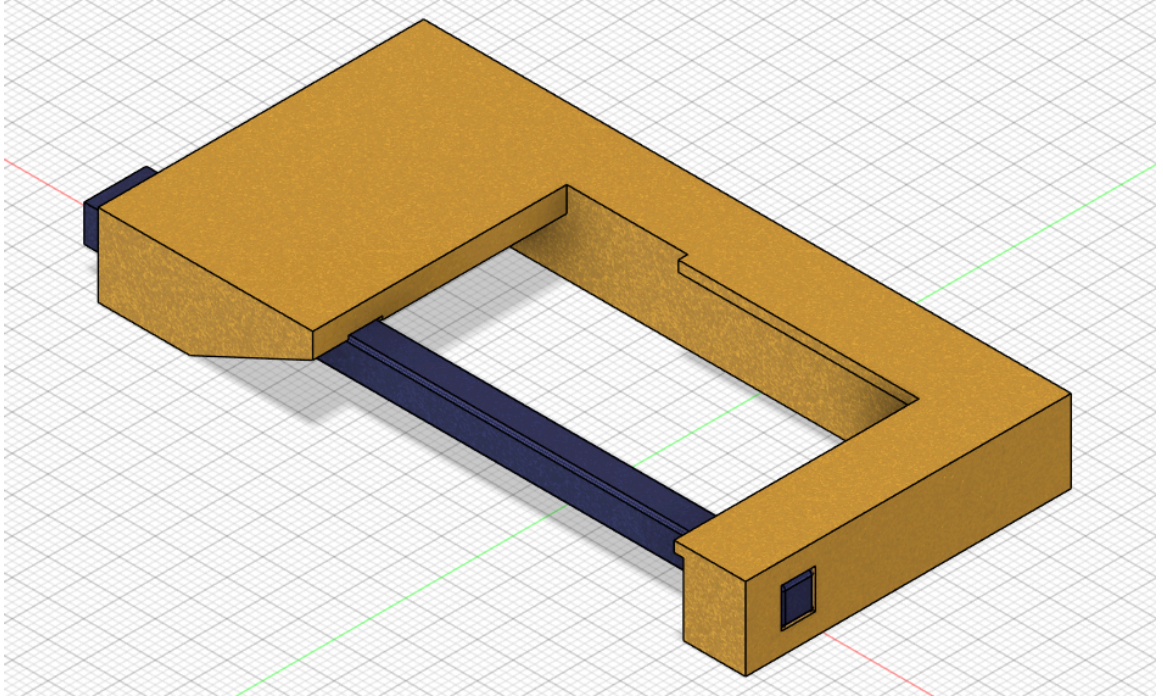


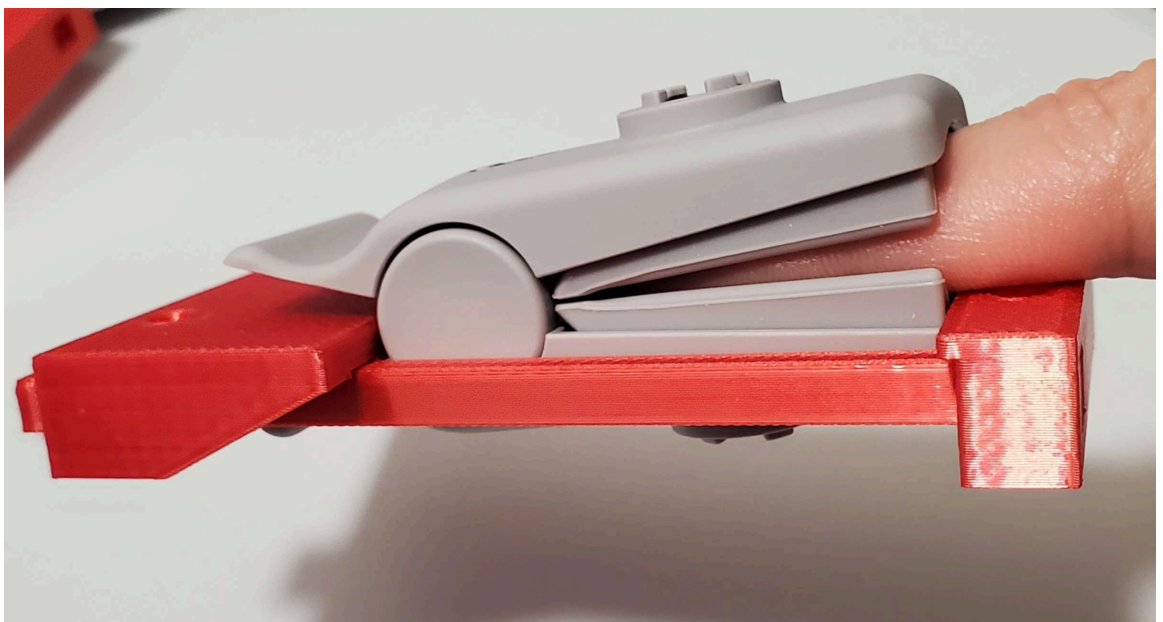
8.2.1.1 Finger Clip Adapter

The Finger Clip Adapter is probably the most crucial part of the whole assembly. The Adult SpO₂ Clip from Philips is designed to work with specific equipment and not to have PCBs mounted to it. So a mount needed to be made so the PPG's circuit board can be firmly attached to the clip while also providing enough room and strength that a person can still place and remove their finger from the device.

The way the mount works is it grips onto one half of the clip. An inverted ramp grips onto one lever of the clip, and a small overhang on the front of the adapter grips onto the lip formed by the plastic shell of the clip and the silicon finger rest. The clip slides into

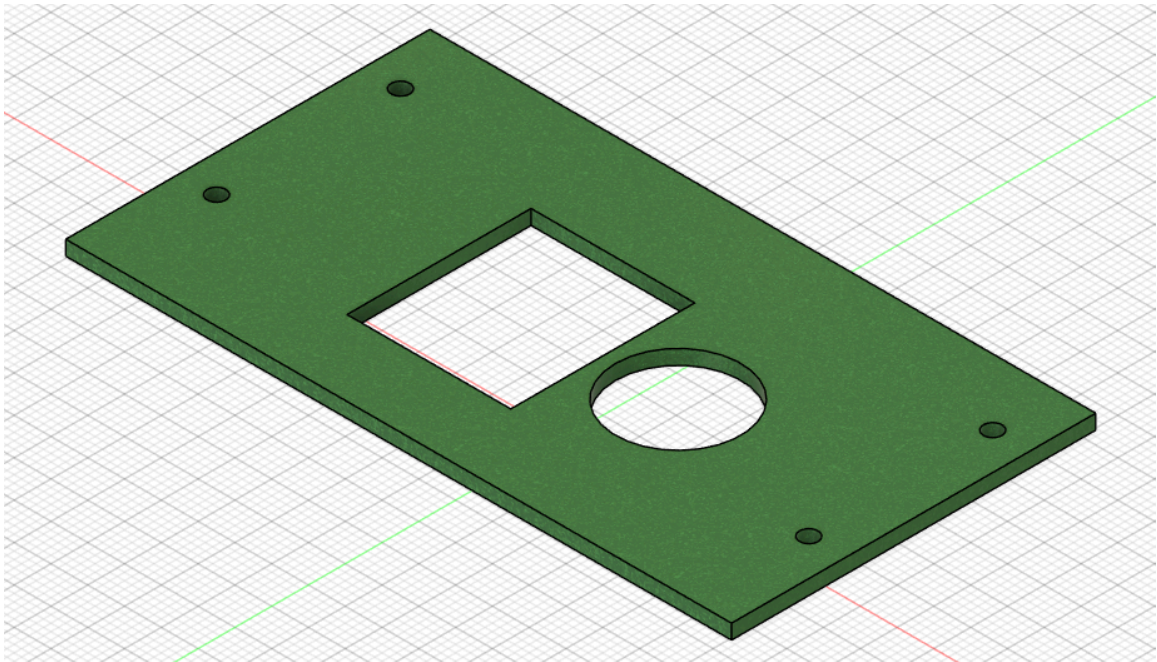
the mount from the side after the pin (blue) is removed. Friction holds the finger clip stable, but the pin as well as other parts of the overall device ensure that it cannot ever move. An additional benefit of this design is that when the clip is attached to the finger, its own spring force in combination with the finger presses the clip against the front lip of the device, forming an even more stable grip. See the images of red prototypes below to better understand how the mount works. heat-set inserts will be placed on the bottom of the mount for the bolts to tighten onto after being pushed through the bolt holes of the other parts.





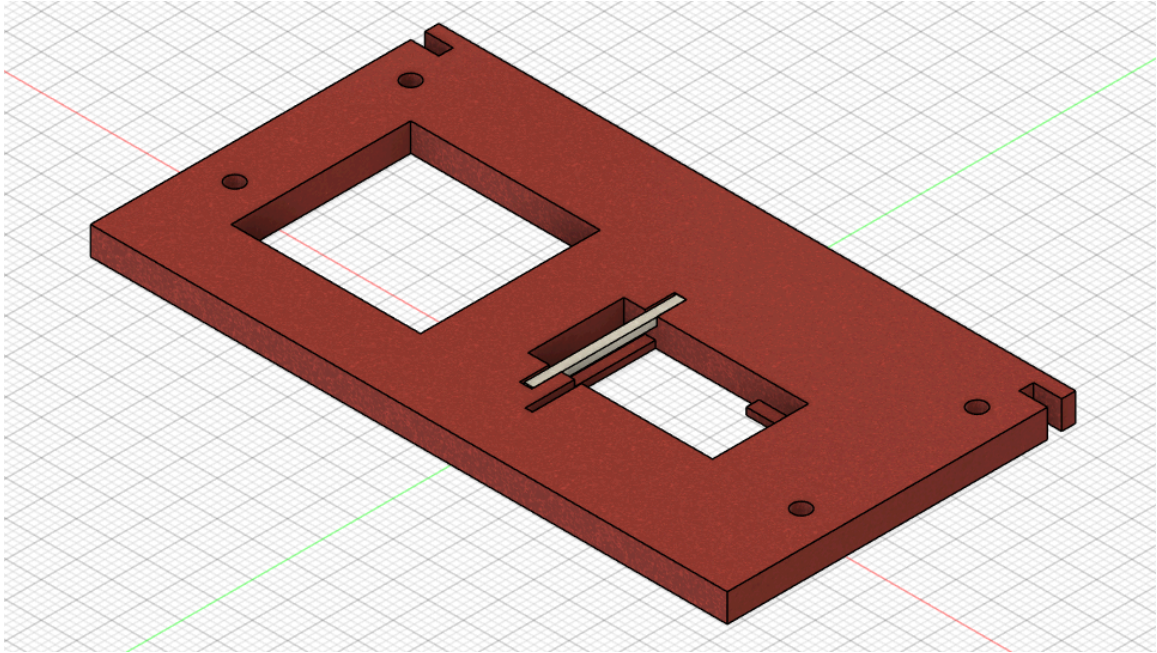
8.2.1.2 Finger Clip Spacer

The Finger Clip Spacer is very simple in appearance, but it serves four critical functions. First, it acts as a spacer so that there is enough room between the outer ring of the lens channel jutting out from the bottom of the clip and the PPG sensor's circuit board. The second function is to help laterally and vertically stabilize the SpO₂ clip. The circle cut-out wraps around the protruding cylinder, while the plastic of the spacer presses against the body of the clip. This circle cut-out also allows it to reduce ambient noise as the circle blocks the gap formed by spacing the PPG sensor from the lens channel. Finally, the spacer also serves as the end of the mounting rail so the PPG does not slide off of the Main Device Body when the sensor is stowed.

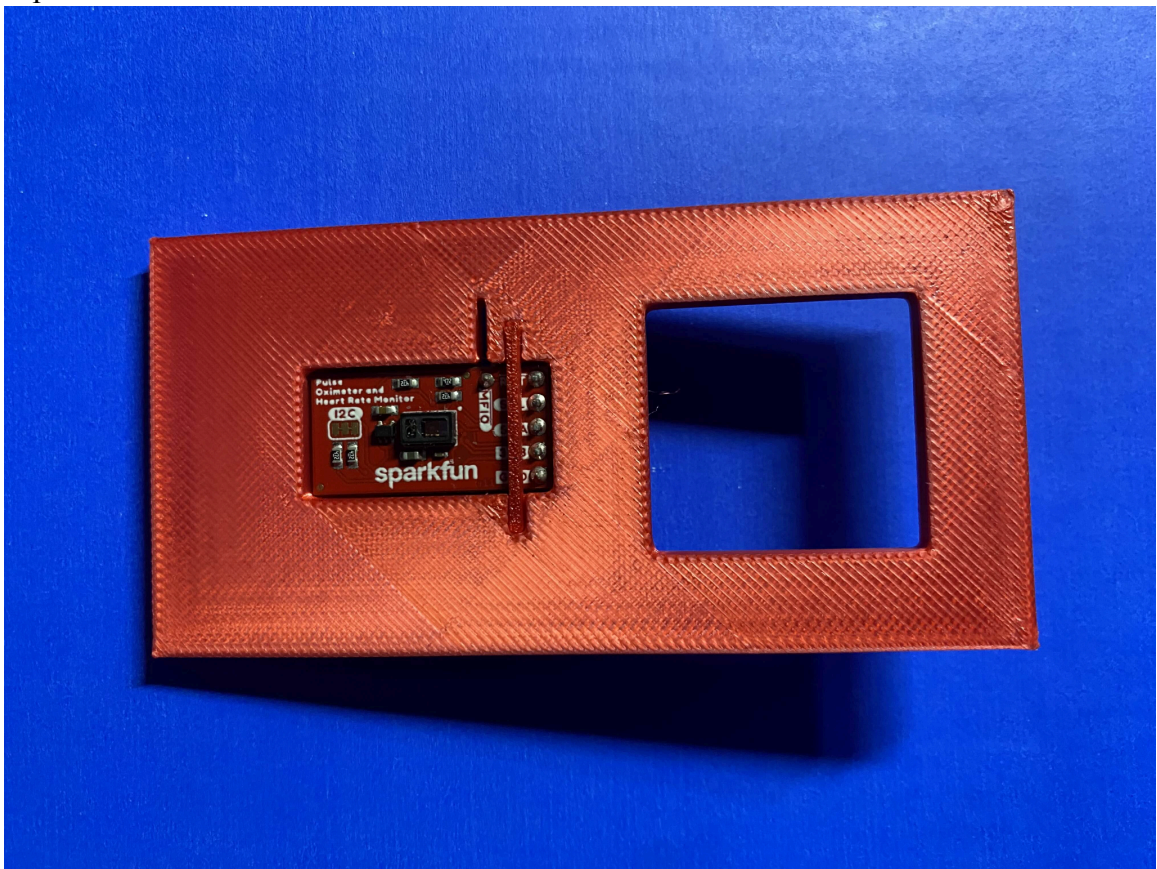


8.2.1.3 PPG Dev Board Holder

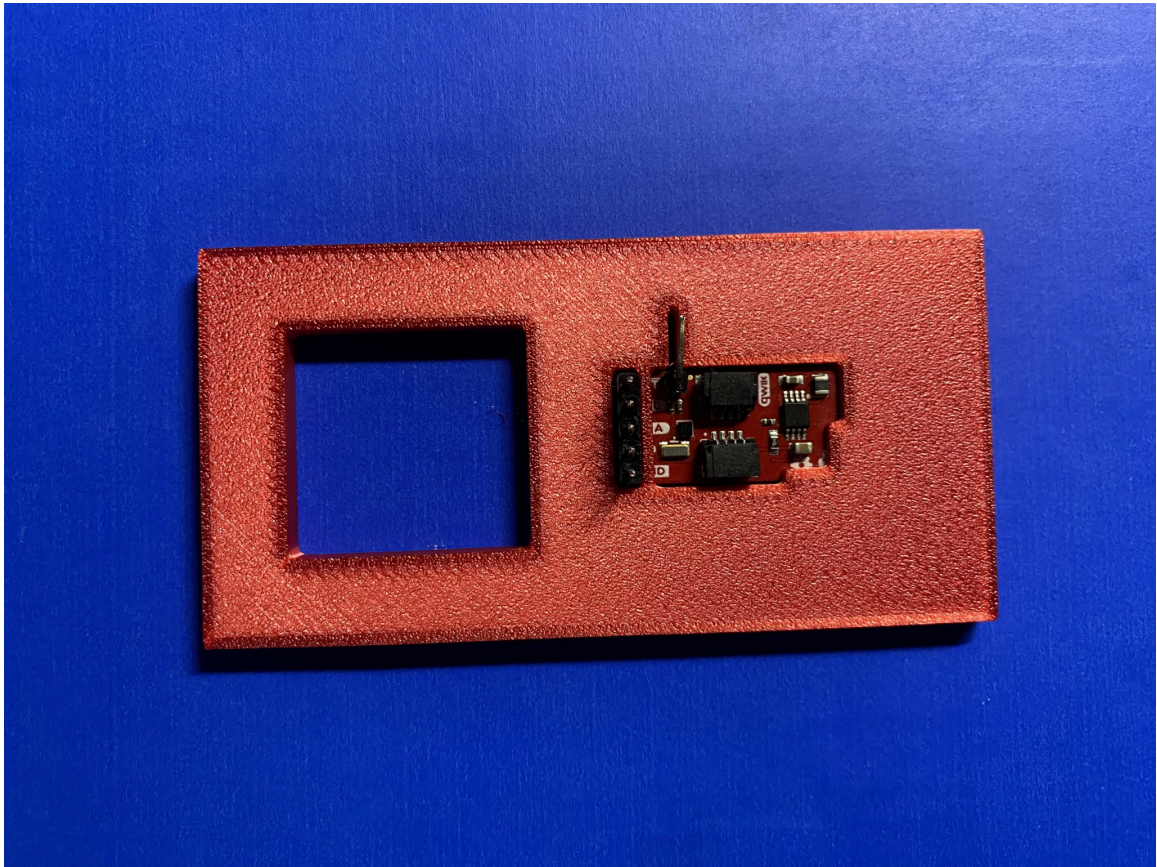
The PPG Dev Board Holder does exactly what it says it does. The PPG development board is placed in the small rectangle in the front. The board is held tightly in place by friction on the four corners as well as a small bar on the bottom that effectively wraps around the plastic of the row of five header pins on one side on the underside of the board. A key bar (white) is placed on top of the PPG board to ensure it will not slide upwards. A small lip is positioned towards the front of the small rectangle in the holder to keep the development board from tipping down. The right angled MFIO header pin has a channel that it can slide down when putting the PPG in the holder. A red prototype is imaged below to better demonstrate how it holds onto the PPG. There are channels on the sides of the part, these are part of the the mounting rails.



Top:

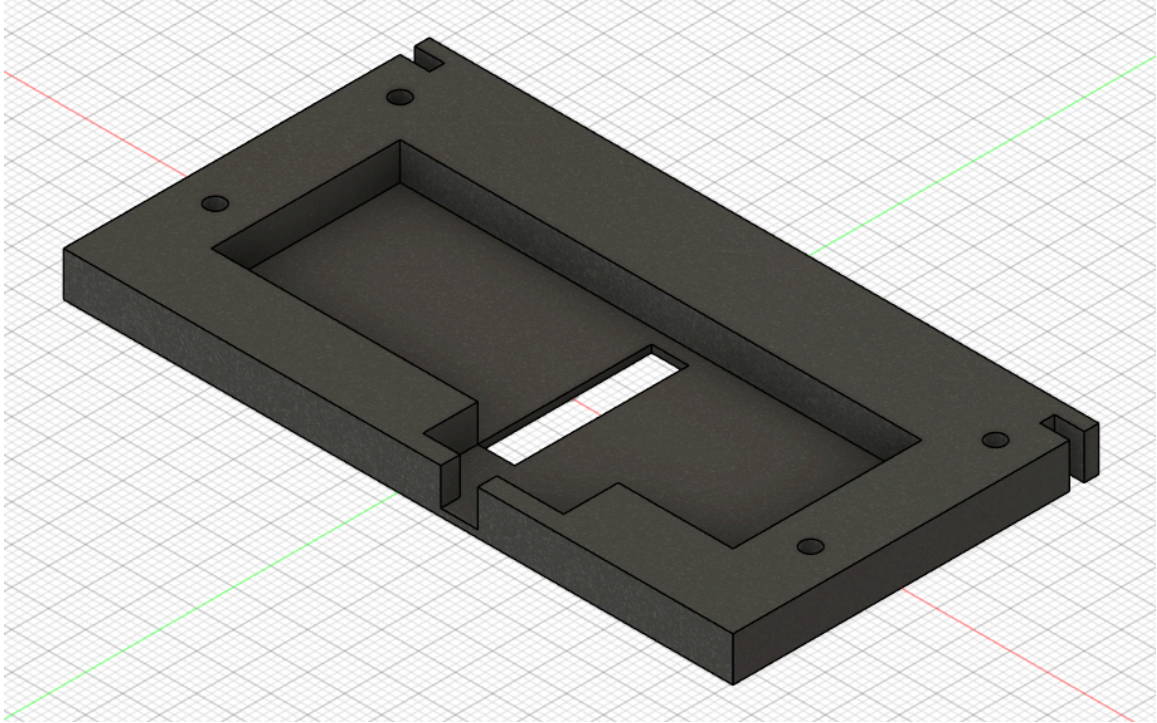


Bottom:



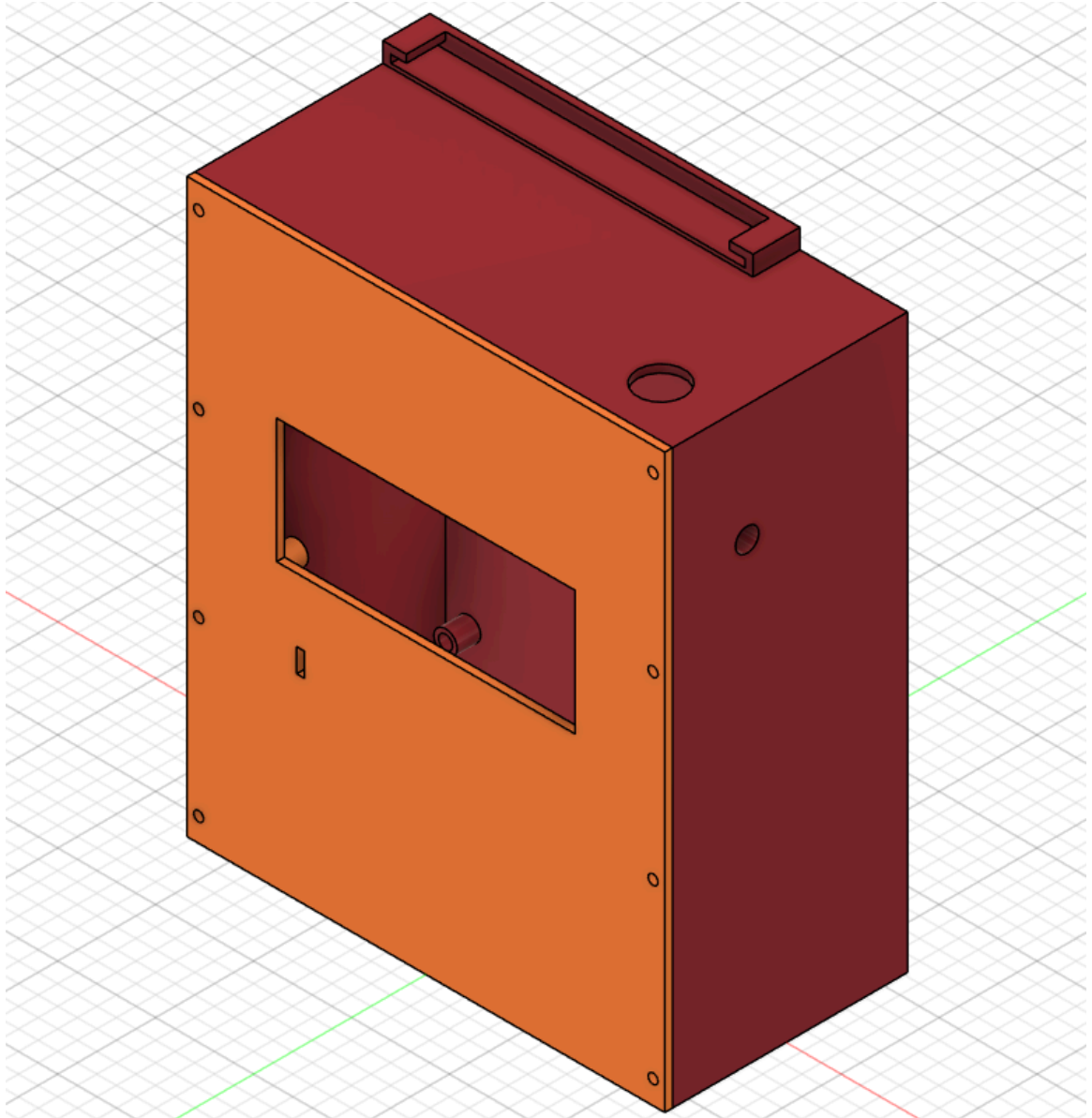
8.2.1.4 Backing Plate

The Backing plate cleans up the device by hiding the exposed circuit board of the PPG sensor; this also helps block out ambient light. It has two cut-outs in it so wires can be attached to the header pins.



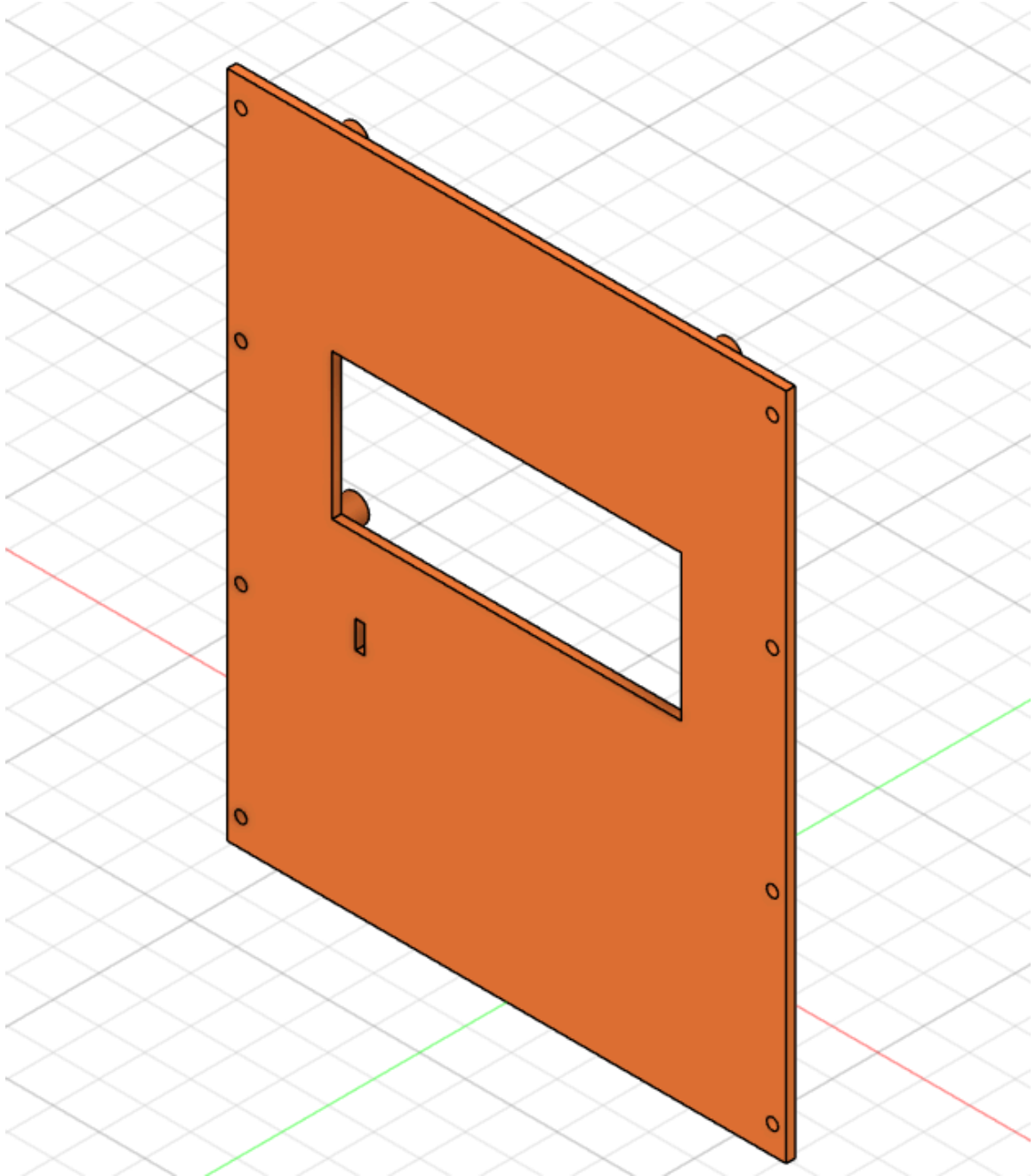
8.2.2 Main Device Body

This is the part of the device the user would carry around or operate while charging. It holds the main components of the PPG Device.



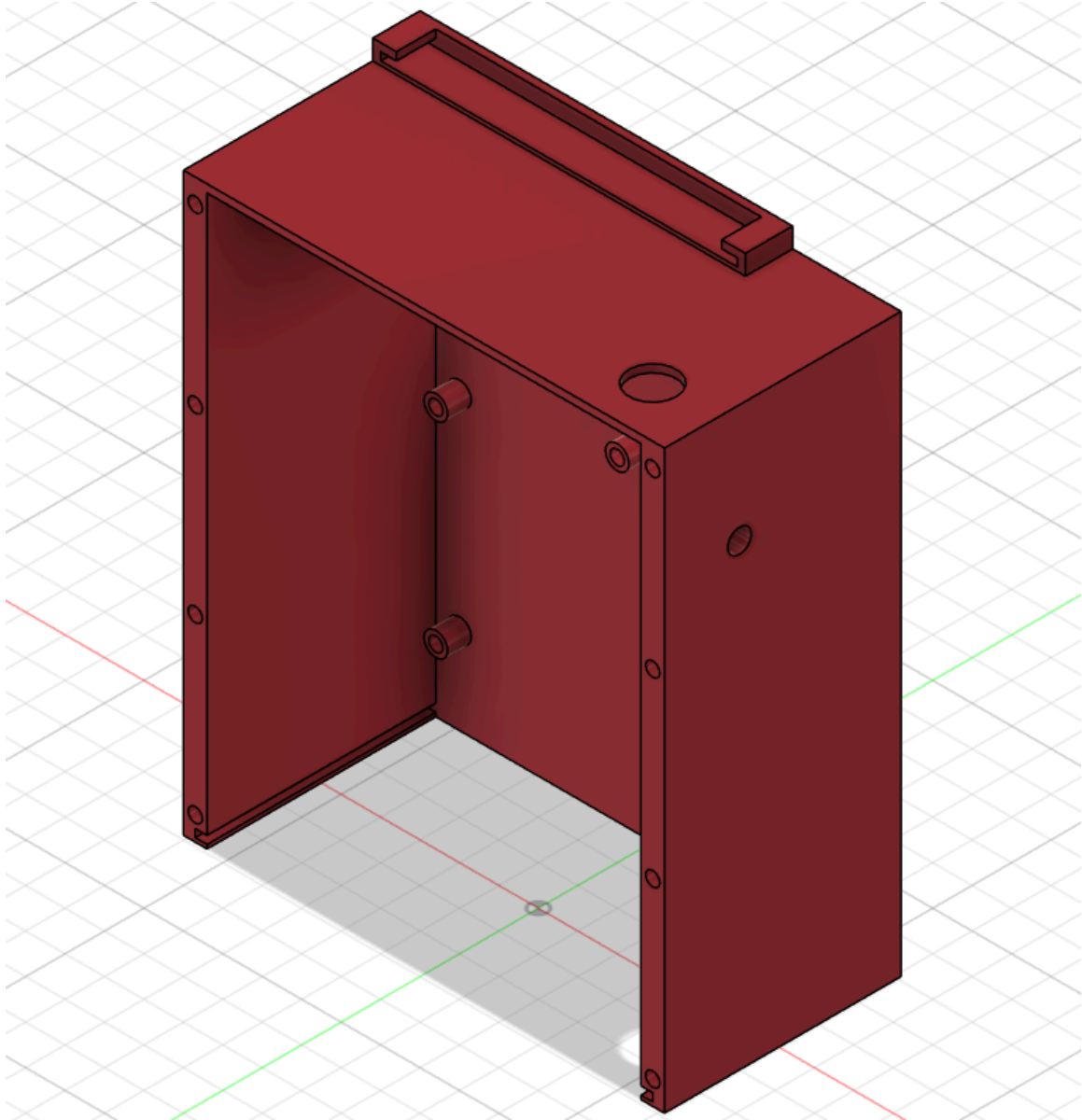
8.2.2.1 Front

The Front piece has mounts for the LCD, RF Module, and the MCU. There are cut-outs for the power switch and to view the LCD screen.



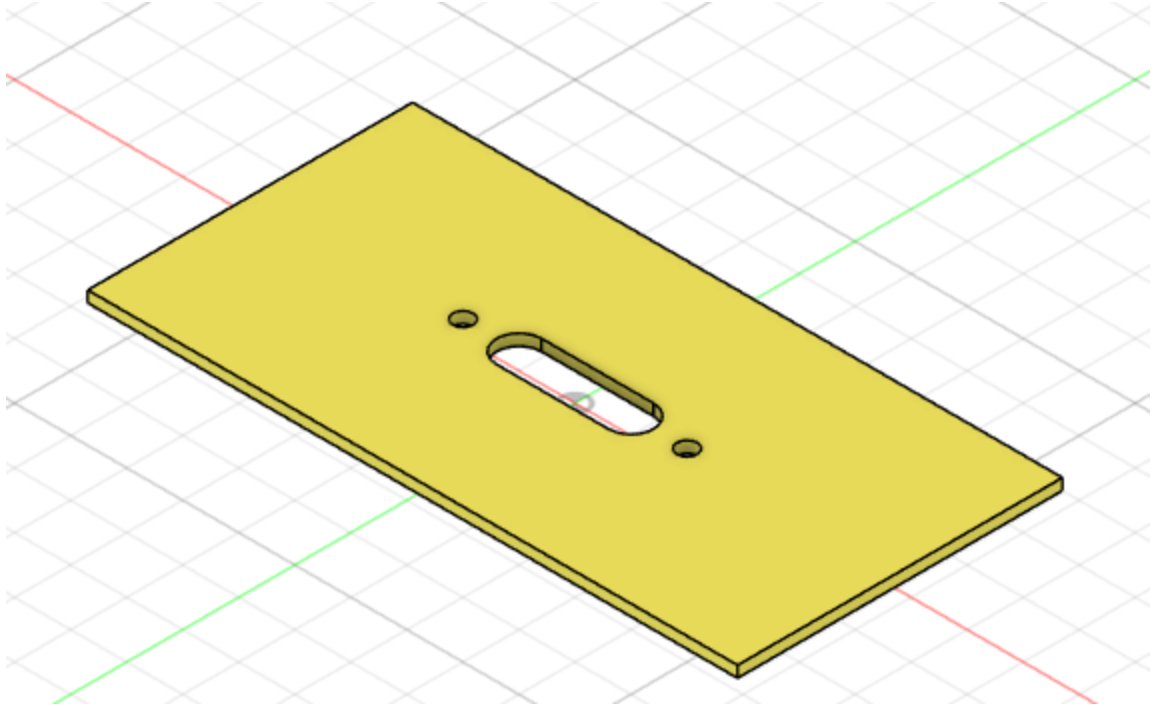
8.2.2.2 Back

The Back piece has mounts for the on-board power supply and the 3V3 regulator. Additionally, there is a rail on top for docking the PPG sensor. A hole is cut out of the top for the antenna, and a hole is cut into the side for the PPG sensor's wires. Heat-set inserts will be placed in the bolt holes. There are rails on the bottom for the bottom plate to slide onto.



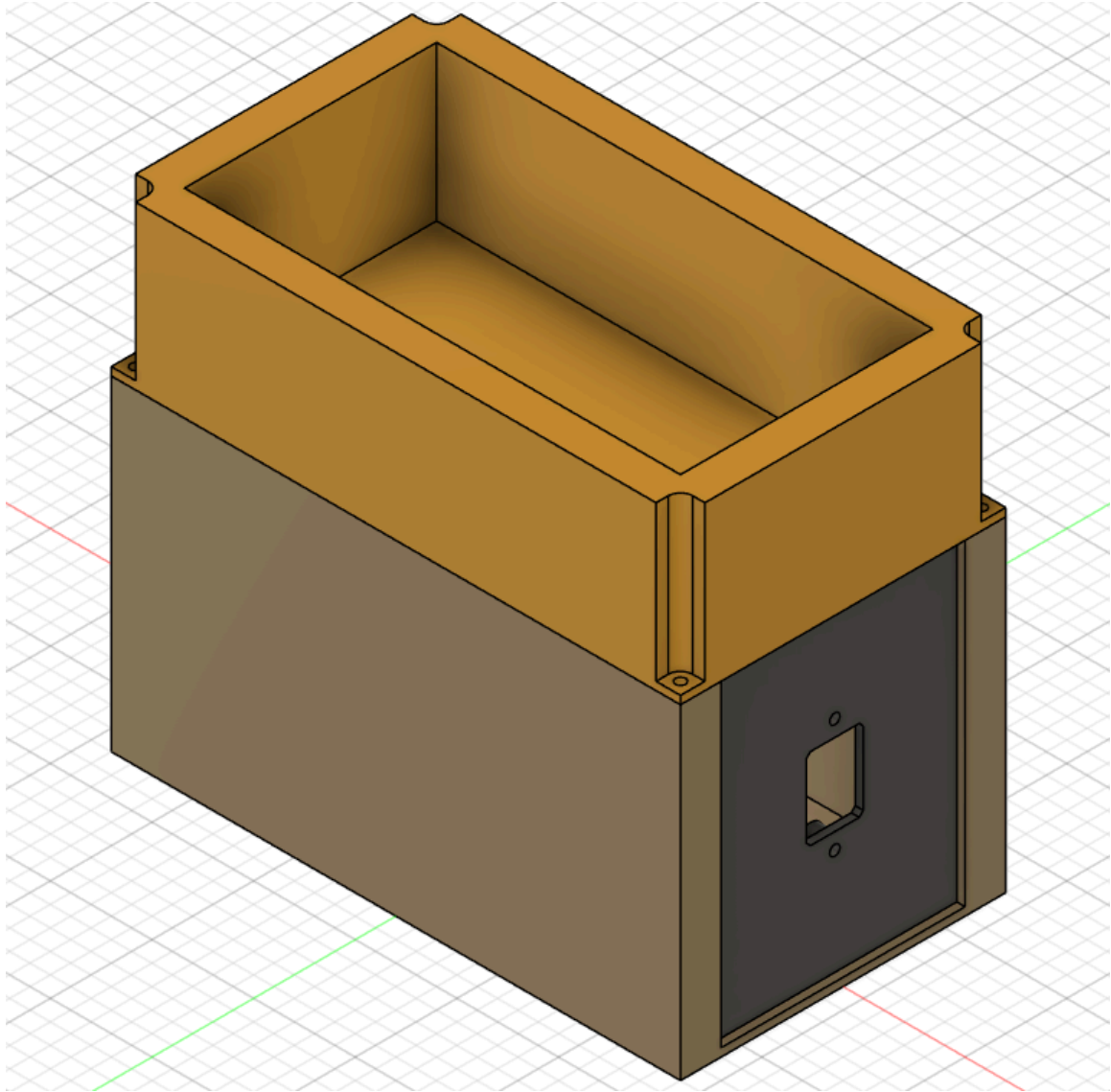
8.2.2.3 Bottom

The Bottom plate provides a mounting surface for the charging contact. It is attached to the PPG device via rails on the bottom of the Back plate.



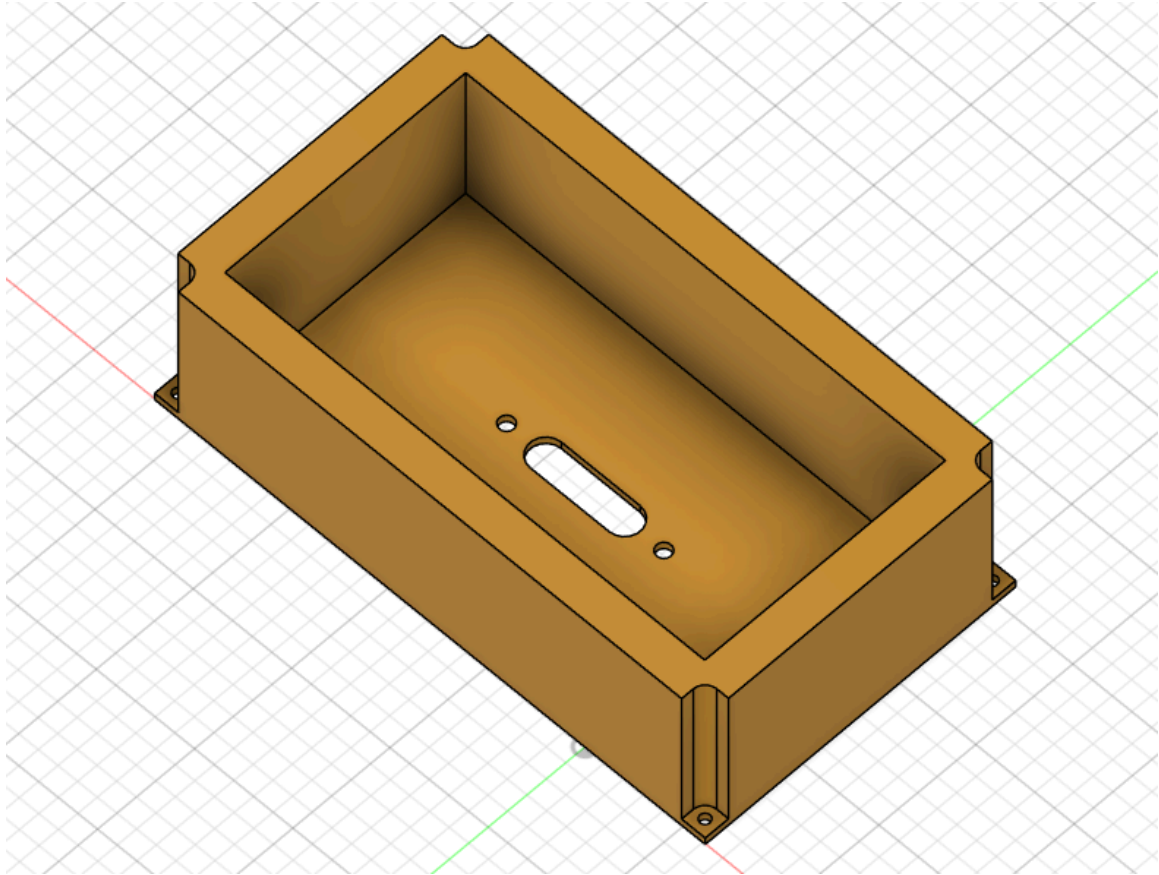
8.2.3 Charging Station

The Charging Station takes wall power and charges the PPG device. It can also serve as a stable location to have a PPG measurement station if the user desires to use it while charging instead of on the move.



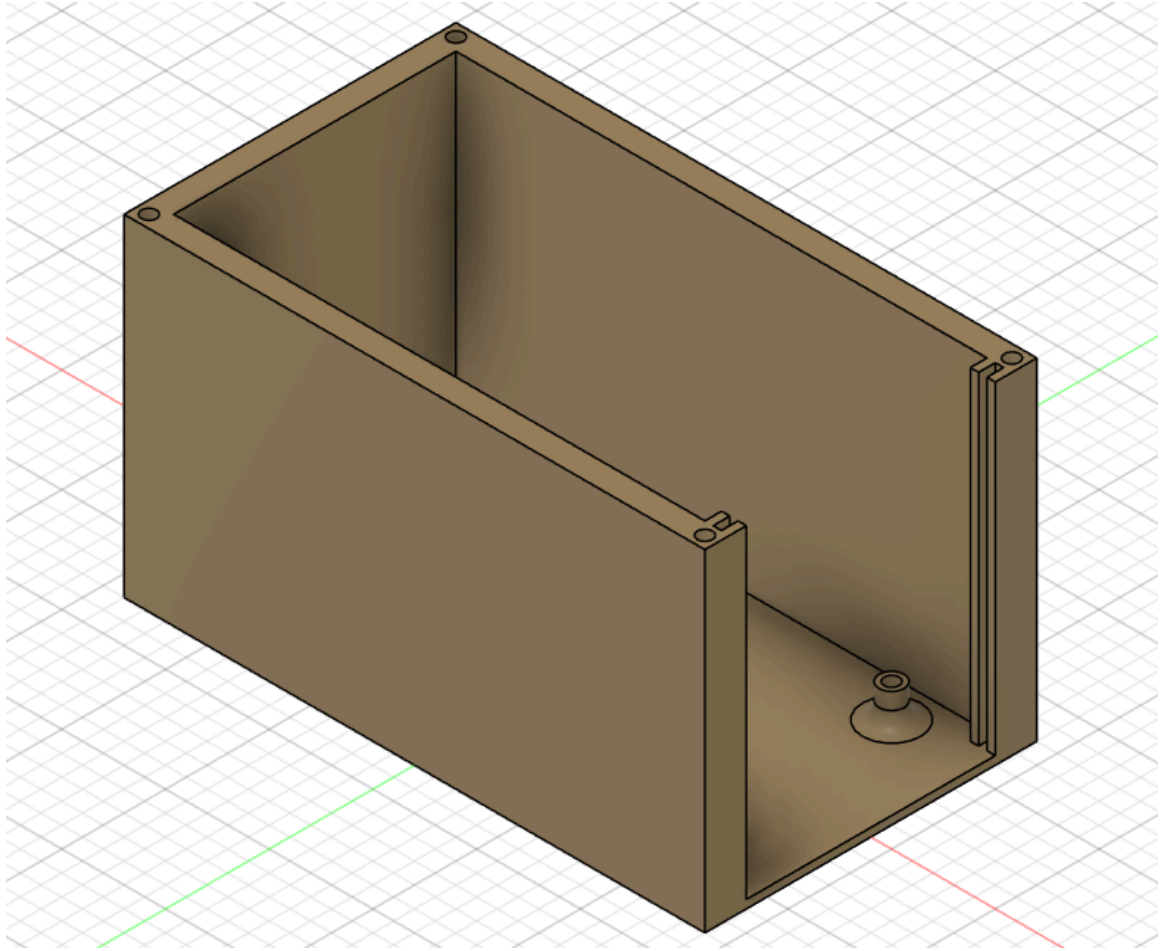
8.2.3.1 Main Device Holder

The Main Device Holder holds the PPG device while charging. It also serves as the contact interface between the device and the charging circuit. A slot was created in the center along with two bolt holes to hold the charging contacts.



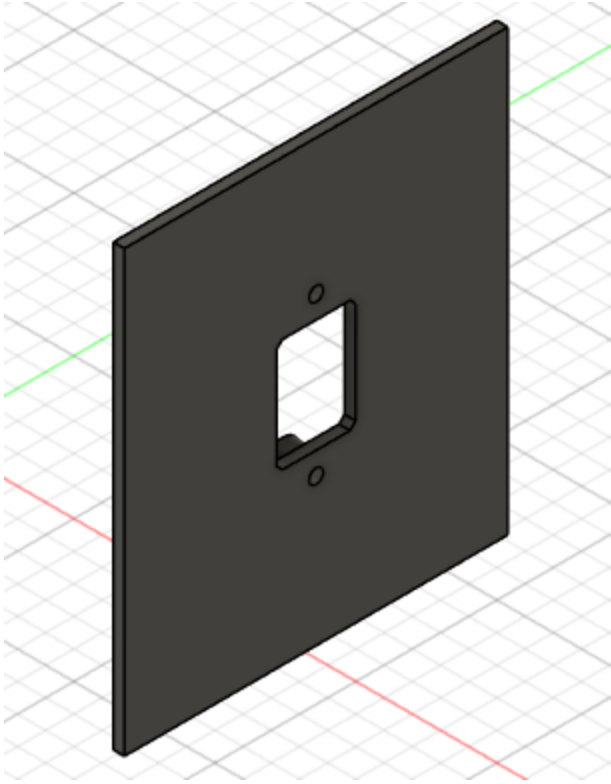
8.2.3.2 Power Supply Board Holder

The Power Supply Board Holder holds the power AC to DC power supply board securely using four bolt mounts created by extruding plastic cylinders and placing heat-set inserts in them.



8.2.3.3 Outlet Wall

The Outlet Wall Slides off of the Power Supply Board Holder via rails. Its main function is to provide a port for the electrical plug. Bolt mounts similar to those in the Power Supply Board Holder allow the plug socket to be firmly attached to the wall. The Outlet Wall is mainly a separate piece from the Power Supply Holder due to the limitations of printing with a 3D printer (printing it as a side wall would mean bridging to create the socket hole), but its removability provides extra room to work with the power supply board.



9. SYSTEM TESTING AND EVALUATION

9.1 Hardware Testing

9.1.1 Power Supply and Battery Charging Test

Proper functionality of the power supply is providing proper power to the load for all current demands. The current demands of the device depend on the charging stage of the battery and the current drawn to the rest of the device. The charging circuit supports up to 1.8A via the power path feature, allowing both the battery and load to receive power at the same time. However, it is not likely that we will reach this. Maximum current draw to charge the battery would be 1A, and we do not expect the device load to draw more than 200mA. So we can expect a nominal max current draw of 1.2A. In this case, we must make sure the power supply stays functional between various current draws.

We can test this system in three separate steps: converter test, regulator test, and charging test. The first test is to check if the switch-mode power supply can sufficiently convert AC wall power into low-voltage DC power. We tested the TNY288 evaluation board with direct connection to the AC line. Proper handling practices were employed since high-voltage AC is dangerous. We tested the board under a no-load condition, multiple light-load conditions, and a standard-load condition. The power supply was able to keep constant output voltage (12.5V) at every condition.

The next test was to do the same procedure, but with our linear regulator at the output of the switch-mode power supply. The regulator will step-down the 12.5V output into the 5V output required by the charging circuit. Under all three conditions, the regulator was also able to continuously output the desired 5V.

Next was the charging test. We used a demo board of the charging circuit to charge our lithium-ion battery. Connecting the board to the battery, along with an input, we saw that the board was able to charge the battery. It is to note that the battery voltage was still in an acceptable range at the beginning of charge, and future testing should be done with more a depleted lithium-ion batteries.

9.1.2 RF Transceiver Test

To test the RF transceiver module, we have the voltage regulators provide 3.3V to drive the CC1101. From there, we utilize the MSP430 to configure the module for a specific modulation scheme. At this step we have the first rung of verification: we write the configuration registers, read them back, and pause the execution of the C code. If we observe the expected values in our Code Composer Studio workspace, we know that SPI is operational. From here, we will transmit packets over SPI using the modulation scheme that we just configured. To verify successful transmission, we will establish a nearby base station running the same modulation scheme in receive mode. If we are able to receive the packets, that means that we have successfully utilized the RF transceiver for data transmission.

9.2 Software Testing

There are plenty of ways to test software, especially with modern tools. Compilers can often find errors within segments of code before runtime. They will often point to specific lines or areas of code that are problematic and how to fix them. However, this doesn't usually cover everything we can encounter when creating a program. Errors during runtime have various ways of tackling the issue. If the programmer is unsure if data is being correctly read, using print statements to show the read values can confirm the validity of the data. In the case of a logic error, print statements can also be used to show where we are in the program's pointer. This is especially useful when conditional statements aren't running when they should and can often point to where issues are.

10. ADMINISTRATIVE CONTENT

10.1 BUDGET AND FINANCING

10.1.1 Actual Expenses

<u>Ethan Denner</u>	
Item	Cost
PPG Sensor Development Board – x2 (w/ shipping)	\$119.08
Total:	
<u>Kai Ford</u>	
Item	Cost
CC1101 Development Board - x4	\$27.81
Quectel YECT003AA (Antenna) - x2	\$13.86
Total:	\$41.67
<u>Tyler Takimoto</u>	
Item	Cost
MCU Development Board	\$27.96
LCD Display	\$9.02
Total:	
<u>Benjamin Will</u>	
Item	Cost
TNY288P Development Board (w/ transformer and extra ICs)	\$113.49
GBU6M	\$2.16
BA50DDOT	\$3.02
Switch Power Socket	\$8.79

Power Cable	\$6.09
18650 Batteries	\$14.98
18650 Battery Case	\$9.19
MCP73871	\$2.41
DW01	\$0.10
FS8205A	\$0.34
TH310J39	\$0.48
Total:	
Group Total:	

10.2 BILL OF MATERIALS

Part Name	Description	Quantity	Unit Cost	Total Cost
MSP430FR2475 Development Board	The dev board for the chip we plan on using	1	\$27.96	\$27.96
LCD w/ HT1621 Display Driver	6-digit, 7-segmented display with drivers	1	\$9.02	\$9.02
TNY288P Development Board	The dev board for the flyback switch we plan on using	1	\$100	\$100
GBU6M	Diode bridge rectifier	1	\$2.16	\$2.16
BA50DDOT	5V linear regulator	2	\$3.02	\$3.02
18650 Lithium-ion Battery	3.7V lithium battery	1	\$14.98	\$14.98
18650 Battery Case	PCB case for 18650 batteries	1	\$9.19	\$9.19
MCP73871	Battery charging IC	2	\$2.41	\$4.82
DW01	Battery protection IC	2	\$0.10	\$0.20

FS8205A	Dual channel NMOS	2	\$0.34	\$0.68
TH310J39	Battery temperature sensing thermistor	2	\$0.48	\$0.96

10.3 PROJECT MILESTONES SD1

Week	Milestone
1-2	Form a group and brainstorm project ideas
3	Begin research, develop Divide and Conquer document and form a committee
4	Meet with advisor, finalize Divide and Conquer document and research specific components
5	Begin 60-page draft, order specific components and begin preliminary circuit design/simulations
6	Acquire components
7	Begin basic testing of individual components (sensors, batteries, etc.)
8	Continue basic testing of individual components
9	Submit 60-page draft, start breadboarding
10-11	Acquire feedback on 60-page draft, finish up breadboard experiments and begin PCB design
12	Start on 120-page document, start PCB design
13	Continue to work on 120-page document and PCB design
14-15	Order first PCBs
16	Submit 120-page document

10.4 PROJECT MILESTONES SD2

Week	Milestone
1	Make edits to 120-page document as directed

2	Board arrives, solder all components
3-4	Troubleshoot any issues with PCB design: fix them in software and reorder
5	Model and 3D-print the housing for the prototype
6-8	Prototype PCB arrives; solder components and test the board, research solutions to any malfunctions
9	Implement solutions
10	Test prototype with implemented solutions
11-15	Test, optimize processes, etc.
16	Demonstrate prototype

10.5 WORK DISTRIBUTION

10.5.1 Paper Contributions

Contributor	Section Headings
Ethan Denner	2.2.1.2 Fingertip Oximeter 2.2.1.3 Handheld Oximeter 2.2.1.4 Wearable Oximeter 2.2.1.5 Related Products' Features Applied to NIMBL's Features 3.1.1.1 Reflective PPG Sensor Technology Comparison and Selection 3.1.1.2 Reflective PPG Sensor Technology Selection and Reasoning 3.1.2.1 PPG Sensor Part Comparison and Selection 3.1.2.2 PPG Sensor Part Comparison Table 3.1.2.9 Wire Harness Connector Part Comparison and Selection 3.1.2.10 Wire Harness Connector Part Selection and Reasoning 4.1.1 OLGA Package 4.2.1 Noise Handling and Digital Signal Processing of the PPG Signal 4.3.2 RoHS Standard

	4.4.1 3D Printability 5.1 Ethan Denner's Application of AI 6.3.1 PPG Sensor Subsystem 6.3.2 MCU Subsystem 6.3.6 Voltage Regulator Subsystem 8.1.2 Voltage Regulator Subsystem 8.1.5 MCU Subsystem 8.2 CAD
Kai Ford	2.4 Hardware Block Diagram 3.1.1.5 RF Technology Comparison 3.1.1.6 RF Technology Comparison Table 3.1.1.7 Antenna Technology Comparison 3.1.1.8 Antenna Technology Comparison Table 3.1.2.3 RF Module Part Comparison 3.1.2.4 RF Module Comparison Table 3.1.2.5 Monopole Antenna Part Comparison 3.1.2.6 Monopole Antenna Part Comparison Table 4.1.2 FCC Part 15 5.2 Kai Ford's Application of AI 6.3.4 Radio Transceiver Description 8.1.1 RF Transceiver Subsystem 9.1.2 RF Transceiver Testing
Tyler Takimoto	2.2.2 Features and Functionality 2.5 Software Flowchart 2.7.1 House of Quality 3.1.1.3 Display Technology Comparison and Selection 3.1.2.7 MCU Part Comparison and Selection 3.1.2.8 MCU Part Comparison Table 3.2 Communication protocol 3.3 Software Comparison and Selection 4.1.5 IEC 62304 4.1.6 IEC 60601 4.2.2 Power Draw 5.3 Tyler Takimoto's Application of AI 6.1 Hardware Design Overview 6.3.3 Display Subsystem 7 Software Design 7.1 Software Design Overview 7.2 Overall System Block Diagram

	7.3 Software Subsystem Design 7.3.1 Sensor Data Subsystem 7.3.2 Power Control Subsystem 7.3.3 Display Subsystem
Benjamin Will	2.3.2 Subsystem Specifications 2.7.1 House of Quality 2.7.2 Estimated Costs Table 3.1.3 Power System 4.1.2 FCC Part 15 4.1.4 10 CFR Part 430 4.3.2 IEC 61000-4 5.4 Benjamin Will's Application of AI 6.3.7 Battery Subsystem 6.3.8 Power Supply Subsystem 8.1.3 Battery Charging Subsystem 8.1.4 Power Supply Subsystem 9.1.1 Power Supply and Battery Charging Test

10.5.2 Design, Assembly, and Testing Contributions

Contributor	Contribution
Ethan Denner	PPG, CAD, 3V3 Reg, MCU Board
Kai Ford	RF Module & Video Editing
Tyler Takimoto	MCU & Software Design
Benjamin Will	Battery Charging/Protection Circuit & Power Supply (Assembly and Test)

APPENDIX A - REFERENCES

- [1] M. Bunn, T. Hooker, and S. Munger, *Infant monitoring device*, U.S. Patent 12,144,648 B2, Nov. 19, 2024. [Online]. Available: <https://patents.google.com/patent/US12144648B2/en>. [Accessed: Sep. 2, 2025].
- [2] Amazon, "Owlet Accessory Monitor with Base Station (Sensor Not Included)." Amazon. [Online]. Available: <https://www.amazon.com/Owlet-Accessory-Monitor-Station-Included/dp/B08R5CHF5P/>. [Accessed: Sep. 2, 2025].
- [3] Google, "Gemini 2.5 Flash." Google. [Online]. Available: <https://gemini.google.com/>. [Accessed: Sep. 4, 2025].
- [4] Morgenthaler, A. B., T. H. E. L. I. T. L. E., S. S. J. C. K. S. O. N. M. B., N. G. R. E. A. S. O. N. S. U. G., L. L. Y. D., C. I. N. G. O. L. F. N. S. O. N., L. P. L., and M. D. E. A. R. S. U. G. "The performance of 11 fingertip pulse oximeters during hypoxemia in healthy human participants with varied, quantified skin pigment." *eBioMedicine*, vol. 102, March 2024, Art. no. 105051.
- [5] "Onyx® Vantage 9590 Finger Pulse Oximeter: Instructions for Use-English," Nonin Medical, Inc., Plymouth, MN, document no. 113634-001-01, 2019. [Online]. Available: https://www.nonin.com/wp-content/uploads/113634-001-01_ENG.pdf. [Accessed: 5 Sep. 2025].
- [6] R. Finnerty, "How to Design a Better Pulse Oximeter," *Analog Devices*, June 1, 2021. [Online]. Available: <https://www.analog.com/en/resources/technical-articles/how-to-design-a-better-pulse-oximeter.html>. [Accessed: 5 Sep. 2025].
- [7] "Nonin PureSAT® SpO2 Averaging," Nonin Medical, Inc. [Online]. Available: <https://www.nonin.com/resource/puresat-spo2-averaging/>. [Accessed: 5 Sep. 2025].
- [8] Nonin Medical, Inc., "Onyx Vantage 9590." Nonin Medical, Inc. [Online]. Available: <https://www.nonin.com/products/9590/>. [Accessed: 4 Sep 2025].
- [9] "Rad-G® Spot-Check Pulse Oximeter: Product Information," Masimo, Irvine, CA, document no. PLM-12397E-0225, 2025. [Online]. Available: <https://www.masimo.com/siteassets/us/documents/pdf/plm-12397e-product-information-rad-g-spot-check-us.pdf>. [Accessed: 5 Sep. 2025].
- [10] "ScanWatch 2," Withings. [Online]. Available: <https://www.withings.com/us/en/scanwatch-2>. [Accessed: 5 Sep. 2025].
- [11] OpenAI, "ChatGPT (GPT-5)." OpenAI. [Online]. Available: <https://chat.openai.com/>. [Accessed: Sep. 4, 2025].

- [12] “Multi-wavelength photoplethysmography method for skin arterial ...,” *PubMed Central*, Sep. 19, 2025. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC5102532/>
- [13] “PPG Theory: Beer-Lambert Law #sleepscience #sleepresearch,” *YouTube*, Sep. 19, 2025. [Online]. Available: <https://www.youtube.com/shorts/yM9VUwrGY34>
- [14] “An ML-Based Approach to Reconstruct Heart Rate from PPG in Presence of Motion Artifacts,” *PubMed Central*, Sep. 19, 2025. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10377343/>
- [15] *How to Design Peripheral Oxygen Saturation (SpO2) and Optical Heart Rate Monitoring (OHRM) Systems Using AFE4403*, Texas Instruments, Sep. 19, 2025. [Online]. Available: <https://www.ti.com/lit/pdf/slaa655>
- [16] “PPG Sensors: The Future of Safety Wearables and Heat Stress Management,” *SlateSafety*, Sep. 19, 2025. [Online]. Available: <https://slatesafety.com/revolutionizing-workplace-safety-ppg-sensors/>
- [17] “Current progress of photoplethysmography and SPO2 for health monitoring,” *PubMed Central*, Sep. 19, 2025. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC6431353/>
- [18] W. B. Gratzer and N. Kollias, “Absorption spectra of oxygenated and deoxygenated hemoglobin between 400 nm and 630 nm,” *ResearchGate*, Sep. 19, 2025. [Online]. Available: https://www.researchgate.net/figure/Absorption-spectra-of-oxygenated-and-deoxygenated-hemoglobin-between-400-nm-and-630-nm_fig2_270050892
- [19] R. Minassian, “Calculating SpO2 using Photoplethysmography (PPG ...),” *Observable*, Sep. 19, 2025. [Online]. Available: <https://observablehq.com/@roupenminassian/calculating-spo2>
- [20] “Perfusion Index (PI) in pulse oximetry: what is good vs. bad?,” *Turner Medical*, Sep. 25, 2025. [Online]. Available: https://www.turnermedical.com/Perfusion_Index_PI_in_pulse_oximetry_what_good_vs_bad_s/161.htm
- [21] “Challenges in PPG amplitude reduction,” *PubMed Central*, Sep. 25, 2025. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC9056464/>
- [22] “Basic principle of PPG sensors working in: (a) transmission, (b) reflection modes,” *ResearchGate*, Sep. 19, 2025. [Online]. Available: https://www.researchgate.net/figure/Basic-principle-of-PPG-sensors-working-in-a-transmission-b-reflection-modes_fig1_347589318
- [23] “Design of an Analog Front-End (AFE) for Photoplethysmography (PPG) Acquisition System,” *Advanced Sciences and Technology Journal*, Sep. 19, 2025.

[Online]. Available:

https://astj.journals.ekb.eg/article_395349_76c9680b729346778b9d01ad4a095b40.pdf

- [24] *Photoplethysmography (PPG) With Integrated AFE for Optical Biosensing*, Texas Instruments, Sep. 19, 2025. [Online]. Available: <https://www.ti.com/lit/pdf/sbat014>
- [25] *AFE4403 Data Sheet, Product Information and Support*, Texas Instruments, Accessed Sep. 19, 2025. [Online]. Available: <https://www.ti.com/product/AFE4403>
- [26] *MAX30102—High-Sensitivity Pulse Oximeter and Heart-Rate Sensor for Wearable Health*, Analog Devices, accessed Sep. 19, 2025. [Online]. Available: <https://www.analog.com/media/en/technical-documentation/data-sheets/MAX30102.pdf>
- [27] “Analysis of the Effect of Red LED and Infrared Flip Flop Frequency on SpO₂ Measurement Accuracy,” *ResearchGate*, Sep. 19, 2025. [Online]. Available: [https://www.researchgate.net/publication/361047481_Analysis_of_the_Effect_of_Red_LED_and_Infrared_Flip_Flop_Frequency_on_SpO₂ Measurement_Accuracy](https://www.researchgate.net/publication/361047481_Analysis_of_the_Effect_of_Red_LED_and_Infrared_Flip_Flop_Frequency_on_SpO2_Measurement_Accuracy)
- [28] “Sensors: PPG,” *SensorWiki.org*, Sep. 19, 2025. [Online]. Available: <https://www.sensorwiki.org/sensors/ppg>
- [29] “Multi-Wavelength Photoplethysmography Device for the Measurement of Pulse Transit Time in the Skin Microvasculature,” *Computing in Cardiology*, Sep. 19, 2025. [Online]. Available: <https://www.cinc.org/archives/2020/pdf/CinC2020-179.pdf>
- [30] “Guidelines for SpO₂ Measurement,” *Analog Devices*, Sep. 19, 2025. [Online]. Available: <https://www.analog.com/en/resources/technical-articles/guidelines-for-spo2-measurement--maxim-integrated.html>
- [31] V. N. D. Le, S. Fronckowiak, and E. Badolato, "A Cost-Effective Method for the Spectral Calibration of Photoplethysmography Pulses: The Optimal Wavelengths for Heart Rate Monitoring," *Sensors*, vol. 25, no. 7, pp. 2311-2311, Apr. 2025. Accessed: Sep. 25, 2025. [Online]. Available: <https://www.mdpi.com/1424-8220/25/7/2311>
- [32] A. A. Kamshilin and N. B. Margaryants, "Origin of Photoplethysmographic Waveform at Green Light," *Physics Procedia*, vol. 86, pp. 72–80, Feb. 2017. Accessed: Sep. 29, 2025. [Online]. Available: https://www.researchgate.net/publication/313863759_Origin_of_Photoplethysmographic_Waveform_at_Green_Light

- [33] Y. Maeda, M. Sekine, T. Tamura, A. Moriya, T. Suzuki, and K. Kameyama, "Comparison of reflected green light and infrared photoplethysmography," in *Annu Int Conf IEEE Eng Med Biol Soc*, 2008, pp. 2270–2272. doi: 10.1109/IEMBS.2008.4649649. Accessed: Sep. 25, 2025. [Online]. Available: <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4649649>
- [34] Y. Maeda, M. Sekine, T. Tamura, and K. Mizutani, "Green Light Photoplethysmography as a Substitute for Heart Rate Variability Monitoring," *Adv. Biomed. Eng.*, vol. 13, pp. 301–306, Oct. 2024. doi: 10.14326/abe.13.301. Accessed: Sep. 25, 2025. [Online]. Available: https://www.researchgate.net/publication/385150096_Green_Light_Photoplethysmography_as_a_Substitute_for_Heart_Rate_Variability_Monitoring
- [35] D. Shao, C. Liu, F. Tsow, Y. Yang, Z. Du, R. Iriya, H. Yu, and N. Tao, "Noncontact Monitoring of Blood Oxygen Saturation Using Camera and Dual-Wavelength Imaging System," *IEEE Trans. Bio-med. Eng.*, vol. 63, no. 6, pp. 1091–1098, Jun. 2016. doi: 10.1109/TBME.2015.2481896. Accessed: Sep. 25, 2025. [Online]. Available: https://www.researchgate.net/publication/282764648_Noncontact_Monitoring_of_Blood_Oxygen_Saturation_Using_Camera_and_Dual-Wavelength_Imaging_System#pf2
- [36] Microsoft, Copilot (Smart Mode, Powered by GPT-5). [Online]. Accessed: Sep. 29, 2025. Available: <https://copilot.microsoft.com/>
- [37] I. Cusini, R. Rinaldi, P. Castiglioni, A. Faini, and F. Villa, "Multi-wavelength SPAD photoplethysmography for cardio-respiratory monitoring," *Front. Phys.*, vol. 11, Art. no. 952103, 2023. doi: 10.3389/fphy.2023.952103. [Online]. Available: <https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2023.952103/full>
- [38] F. Mohagheghian et al., "Optimized Signal Quality Assessment for Photoplethysmogram Signals Using Feature Selection," *IEEE Trans. Biomed. Eng.*, vol. 69, no. 9, pp. 2982–2993, Sept. 2022, doi: 10.1109/TBME.2022.3158582. [Online]. Available: <https://ieeexplore.ieee.org/document/9733241>
- [39] K. Matsumura, P. Rolfe, J. Lee, and T. Yamakoshi, "iPhone 4s Photoplethysmography: Which Light Color Yields the Most Accurate Heart Rate and Normalized Pulse Volume Using the iPhysioMeter Application in the Presence of Motion Artifact?," *PLOS ONE*, vol. 9, Art. no. e91205, Mar. 2014. doi: 10.1371/journal.pone.0091205. [Online]. Available: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0091205>
- [40] K. Setchfield, A. Gorman, A. H. R. W. Simpson, M. G. Somekh, and A. J. Wright, "Effect of skin color on optical properties and the implications for medical optical technologies: a review," *J. Biomed. Opt.*, vol. 29, no. 1, Art. no. 010901, Jan.

2024. doi: 10.1117/1.JBO.29.1.010901. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10807857/>.
- [41] W. Ao, "Enhancing Kalman Filter Performance for PPG Signal Denoising: Adaptive Integration of Accelerometer and Gyroscope Data," in Proc. 5th Int. Conf. Signal Process. Mach. Learn., vol. 133, Jan. 2025, pp. 142–148. doi: 10.54254/2755-2721/2025.20638. [Online]. Available: <https://www.ewadirect.com/proceedings/ace/article/view/20638>.
- [42] F. Shaffer and J. P. Ginsberg, "An Overview of Heart Rate Variability Metrics and Norms," Front. Public Health, vol. 5, Art. no. 258, Sep. 2017. doi: 10.3389/fpubh.2017.00258. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC5624990/>.
- [43] Heart rate variability. Wikipedia. [Online]. Available: https://en.wikipedia.org/wiki/Heart_rate_variability. [Accessed: Oct. 9, 2025].
- [44] J. Liu, Y. Li, X. -R. Ding, W. -X. Dai and Y. -T. Zhang, "Effects of cuff inflation and deflation on pulse transit time measured from ECG and multi-wavelength PPG," 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan, Italy, 2015, pp. 5973-5976. doi: 10.1109/EMBC.2015.7319752. [Online]. Available: <https://ieeexplore.ieee.org/abstract/document/7319752>.
- [45] J. Liu, Y. -T. Zhang, X. -R. Ding, W. -X. Dai and N. Zhao, "A preliminary study on multi-wavelength PPG based pulse transit time detection for cuffless blood pressure measurement," in 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Orlando, FL, USA, 2016, pp. 615-618. doi: 10.1109/EMBC.2016.7590777. [Online]. Available: <https://ieeexplore.ieee.org/abstract/document/7590777>.
- [46] R. R. Anderson and J. A. Parrish, "The Optics of Human Skin," J. Invest. Dermatol., vol. 77, no. 1, pp. 13-19, 1981. doi: 10.1111/1523-1747.ep12479191. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0022202X15461251>.
- [47] D. T. Delpy and M. Cope, "Quantification in tissue near-infrared spectroscopy," Philos. Trans. R. Soc. Lond. B Biol. Sci., vol. 352, no. 1354, pp. 649–659, Jun. 1997. doi: 10.1098/rstb.1997.0046. [Online]. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC1691964/>.
- [48] P. Mohapatra, P. S. Premkumar, and M. Sivaprakasam, "A Yellow–Orange Wavelength-Based Short-Term Heart Rate Variability Measurement Scheme for Wrist-Based Wearables," IEEE Trans. Instrum. Meas., vol. 67, no. 5, pp. 1091-1101, May 2018. doi: 10.1109/TIM.2017.2786677. [Online]. Available: <https://ieeexplore.ieee.org/abstract/document/8253824>.

- [49] P. Mohapatra, S. P. Preejith, and M. Sivaprakasam, "A novel sensor for wrist based optical heart rate monitor," in 2017 IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC), Turin, Italy, 2017, pp. 1-6. doi: 10.1109/I2MTC.2017.7969842. [Online]. Available: <https://ieeexplore.ieee.org/document/7969842>.
- [50] E. Shchelkanova, L. Shchapova, A. Shchelkanov, and T. Shibata, "Blue as an Underrated Alternative to Green: Photoplethysmographic Heartbeat Intervals Estimation under Two Temperature Conditions," *Sensors*, vol. 21, no. 12, Art. no. 4241, Jun. 2021. [Online]. Available: <https://www.mdpi.com/1424-8220/21/12/4241>
- [51] J. Lee, K. Matsumura, K. Yamakoshi, P. Rolfe, S. Tanaka, and T. Yamakoshi, "Comparison between red, green and blue light reflection photoplethysmography for heart rate monitoring during motion," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Osaka, Japan, 2013, pp. 1724–1727. doi: 10.1109/EMBC.2013.6609852. Available: <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6609852>
- [52] C.-H. Shen, W.-L. Chen, and J.-J. Wu, "Research on Multiple Spectral Ranges with Deep Learning for SpO2 Measurement," *Sensors*, vol. 22, no. 1, p. 328, Jan. 2022. doi: 10.3390/s22010328. Available: <https://pmc.ncbi.nlm.nih.gov/articles/PMC8749643/>.
- [53] S. J. Barker, J. Curry, D. Redford, and S. Morgan, "Measurement of carboxyhemoglobin and methemoglobin by pulse oximetry: A human volunteer study," *Anesthesiology*, vol. 105, no. 5, pp. 892–897, Dec. 2006. doi: 10.1097/00000542-200611000-00008. Available: https://www.researchgate.net/publication/6730103_Measurement_of_Carboxyhemoglobin_and_Methemoglobin_by_Pulse_Oximetry.
- [54] U.S. Food and Drug Administration, "Masimo Radical-7 Pulse CO-Oximeter," Premarket Notification 510(k) K080238, Feb. 11, 2008. Available: https://www.accessdata.fda.gov/cdrh_docs/pdf8/K080238.pdf.
- [55] M. Barud, W. Dabrowski, D. Siwicki-Gieroba, C. Robba, M. Bielacz, and R. Badenes, "Usefulness of Cerebral Oximetry in TBI by NIRS," *J. Clin. Med.*, vol. 10, no. 13, p. 2938, Jul. 2021. doi: 10.3390/jcm10132938. Available: <https://www.mdpi.com/2077-0383/10/13/2938>.
- [56] D. A. Davydov, G. S. Budylin, A. V. Baev, D. V. Vaipan, E. M. Seredenina, A. A. Kamalov, and E. A. Shirshin, "Skin dehydration monitoring with optical spectroscopy allows assessment of water content in the organism: Thermal and physical loads, diuretic therapy," *J. Biophotonics*, vol. 18, no. 6, p. e202300509, Jan. 2024. doi: 10.1002/jbio.202300509. Available: <https://onlinelibrary.wiley.com/doi/full/10.1002/jbio.202300509>.
- [57] Lyna, "What are the key differences between segment LCD and dot matrix LCD? - hua xian jing," Hua Xian Jing: 13 Years LCD & OLED Module Source

Manufacturer,
<https://huaxianjing.com/differences-between-segment-lcd-and-dot-matrix-lcd>
(accessed Oct. 14, 2025).

- [58] *MAX30101 High-Sensitivity Pulse Oximeter and Heart-Rate Sensor for Wearable Health* (Rev 3: 6/20), Maxim Integrated. [Online]. Available:
<https://www.analog.com/media/en/technical-documentation/data-sheets/MAX30101.pdf>. [Accessed: Oct. 1, 2025].
- [59] *MAXM86161 Single-Supply Integrated Optical Module for HR and SpO₂ Measurement* (Rev 1: 4/23), Analog Devices, Inc. [Online]. Available:
<https://www.analog.com/media/en/technical-documentation/data-sheets/maxm86161.pdf>. [Accessed: Oct. 1, 2025].
- [60] *MAX86916 Integrated Optical Sensor Module for Mobile Health* (Rev 0: 10/19), Maxim Integrated. [Online]. Available:
<https://www.analog.com/media/en/technical-documentation/data-sheets/MAX86916.pdf>. [Accessed: Oct. 1, 2025].
- [61] **Analog Devices**, “Organic Land Grid Array (OLGA) and Its Applications,” **Design Note 1**, Apr. 2017. [Online]. Available:
<https://www.analog.com/en/resources/design-notes/organic--land-grid-array-olga-and-its-applications.html>
- [62] **Analog Devices**, “MAX32664 Ultra-Low Power Biometric Sensor Hub,” **Data Sheet (Rev 0)**, Apr. 2018. [Online]. Available:
<https://www.analog.com/media/en/technical-documentation/data-sheets/MAX32664.pdf>
- [63] **JEDEC Solid State Technology Association**, “About JEDEC.” [Online]. Available:
<https://www.jedec.org/about-jedec> (Accessed: Oct. 24, 2025).
- [64] **JEDEC Solid State Technology Association** and **IPC**, **IPC/JEDEC J-STD-020E**, “Moisture/Reflow Sensitivity Classification for Nonhermetic Surface Mount Devices,” **Jan. 2022**. [Online]. Available:
<https://www.jedec.org/standards-documents/docs/j-std-020e?destination=node/8433>
- [65] European Commission, "RoHS Directive," Environment - European Commission, Dec. 7, 2023. [Online]. Available:
https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en. [Accessed: Oct. 31, 2025].
- [66] European Parliament and the Council of the European Union, "Directive 2011/65/EU of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast)," *Official Journal of the European Union*, vol. L 174, pp. 88–110, Jul. 1, 2011. [Online]. Available:

<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0065>.
[Accessed: Oct. 31, 2025].

- [67] Molex, LLC, "Micro-Lock Plus Connectors," *Molex*. [Online]. Available: <https://www.molex.com/en-us/products/connectors/wire-to-board-connectors/micro-lock-plus-connectors>. [Accessed: Oct. 26, 2025].
- [68] Molex, LLC, "Micro-Lock Plus PCB Header, Part 2045290471," *Molex*. [Online]. Available: <https://www.molex.com/en-us/products/part-detail/2045290471>. [Accessed: Oct. 26, 2025].
- [69] Molex, LLC, "Pico-Lock Connectors," *Molex*. [Online]. Available: <https://www.molex.com/en-us/products/connectors/wire-to-board-connectors/pico-lock-connectors>. [Accessed: Oct. 26, 2025].
- [70] Molex, LLC, "1.50mm Pitch, Pico-Lock PCB Header, Part 5040500491," *Molex*. [Online]. Available: <https://www.molex.com/en-us/products/part-detail/5040500491>. [Accessed: Oct. 26, 2025].
- [71] JST Sales America, Inc., "GH connector," *JST Sales America*. [Online]. Available: <https://www.jst.com/products/crimp-style-connectors-wire-to-board-type/gh-connector/>. [Accessed: Oct. 26, 2025].
- [72] K. de Naoum and M. Conniff, "All About PLA 3D Printing Filament: Composition, Properties, Differences," *Xometry*, Jun. 26, 2025. [Online]. Available: <https://www.xometry.com/resources/3d-printing/pla-3d-printing-filament/>. [Accessed: Oct. 30, 2025].
- [73] "PLA," *Simplify3D*, 2025. [Online]. Available: <https://www.simplify3d.com/resources/materials-guide/pla/>. [Accessed: Oct. 30, 2025].
- [74] K. de Naoum and R. Piccoli, "All About PETG 3D Printing Filament: Materials, Properties, Definition," *Xometry*, Jul. 22, 2025. [Online]. Available: <https://www.xometry.com/resources/3d-printing/petg-3d-printing-filament/>. [Accessed: Oct. 30, 2025].
- [75] "PCTG: its iterations and connection with PET-G," *Spectrum Filaments*, 2025. [Online]. Available: <https://spectrumfilaments.com/en/pctg-its-iterations-and-connection-with-pet-g/>. [Accessed: Oct. 30, 2025].
- [76] "What Is PCTG Filament? Benefits, Uses & Comparison," *3D-Fuel*. [Online]. Available: <https://www.3dfuel.com/blogs/news/what-is-pctg-filament-benefits-uses-comparison>

[on?srsId=AfmBOoq_TjRu5bhoUC4hO0sqoTl2t9WiZXQGQyndrmB64IcCJjyZ2a_](https://www.3dxttech.com/blogs/featured/pctg-vs-petg-which-filament-delivers-superior-performance). [Accessed: Oct. 30, 2025].

- [77] 3DXTECH, "PCTG vs PETG: Which Filament Delivers Superior Performance?" *3DXTECH* Blog, May 28, 2025. [Online]. Available: <https://www.3dxttech.com/blogs/featured/pctg-vs-petg-which-filament-delivers-superior-performance>. [Accessed: Oct. 30, 2025].
- [78] Bluetooth SIG, "Understanding Bluetooth® range," *Bluetooth® Technology Website*, accessed October 30, 2025. Available: <https://www.bluetooth.com/learn-about-bluetooth/key-attributes/range/>
- [79] Texas Instruments, *Decoupling Capacitors*, Application Note SLPA010, Texas Instruments, 2014. Available: https://www.ti.com/content/dam/videos/external-videos/de-de/9/3816841626001/6313253251112.mp4/subassets/notes-decoupling_capacitors.pdf
- [80] Texas Instruments, "Design Note DN017 — CC11xx 868/915 MHz RF Matching (Rev A)," Texas Instruments, Dallas, TX, USA, 2008. [Online]. Available: <https://www.ti.com/lit/pdf/swra168>
- [81] Quectel Wireless Solutions Co., Ltd., YECT003AA External Cellular Antenna Datasheet, Version 3.0, Jul. 2022. Available: https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/5871/Quectel_Antenna_YECT003AA_Datasheet_V3.0.pdf
- [82] NEARSON Inc., "S161XX-915R – 900 MHz ISM Band Antenna (Right Angle Series)," Datasheet, July 21 2015. [Online]. Available: https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/1146/S161xx-915R_Dwg_7-21-15.pdf
- [83] Abracon LLC, AEACAC054010-S915 LPWA/ISM External Antenna Datasheet, revised January 24 2019. Available: <https://www.mouser.com/datasheet/3/184/1/AEACAC054010-S915.pdf>
- [84] Skogvang, K. & Hellan, S., "CC11xx Settings for FCC 15.247 Solutions," Design Note DN006, Texas Instruments, SWRA123B, Aug. 2010.
- [85] Texas Instruments, *CC1101 Low-Power Sub-1 GHz RF Transceiver*, Datasheet, SWRS061H, Rev. H, Texas Instruments Incorporated, Dallas, TX, USA, 2013. Available: <https://www.ti.com/lit/ds/symlink/cc1101.pdf>
- [86] IEEE Std C95.1-2019, "Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz," IEEE, IEEE Xplore Doc. No. 8859679, Oct. 4 2019. Available: <https://ieeexplore.ieee.org/document/8859679>
- [87] A. Bhattacharjee, msp430_cc1101_energia_v2, GitHub repository, May 23 2021. Available: https://github.com/abhra0897/msp430_cc1101_energia_v2
- [88] Batteries Inc., "What Are Alkaline Batteries?," Batteries Inc., <https://batteriesinc.net/what-are-alkaline-batteries/> (accessed Nov. 23, 2025).
- [89] K. U. Hasan. "Alkaline Batteries: How They Work, Their Chemistry, And Charge Explained." TheBatteryTips.com. <https://thebatterytips.com/battery-specifications/how-does-a-alkaline-battery-work/> (accessed Nov. 23, 2025).

- [90] B. Ryan. "Characteristics and Properties of Alkaline Batteries." Battery Skills. <https://www.batteryskills.com/characteristics-and-properties-of-alkaline-batteries/> (accessed Nov. 23, 2025).
- [91] "Rechargeable alkaline battery." chemeuropa.com. https://www.chemeuropa.com/en/encyclopedia/Rechargeable_alkaline_battery.html (accessed Nov. 23, 2025).
- [92] ERSa Electronics. "NiMH (Nickel-Metal-Hydride) Battery: A Complete Guide." ERSa Electronics. <https://www.ersaelectronics.com/blog/nimh-nickel-metal-hydride-battery-a-complete-guide> (accessed Nov. 23, 2025).
- [93] Mesha. "How Does a NiMH Battery Work? Understanding Its Working Principle and Key Features." TYCORUN Energy. <https://www.tycorunenergy.com/how-does-a-nimh-battery-work/> (accessed Nov. 23, 2025).
- [94] Semitech Technology Limited. "Battery Comparison: Lithium-ion vs. Nickel-Metal Hydride vs. Alkaline." Semitech Technology. <https://www.semitech-technology.com/news/battery-comparison:-lithium-ion-vs.-nickel-metal-hydride-vs.-alkaline.html> (accessed Nov. 23, 2025).
- [95] "Lithium-ion Battery – How it works." Electricity & Magnetism. <https://www.electricity-magnetism.org/electric-battery/lithium-ion-battery-how-it-works/> (accessed Nov. 23, 2025).
- [96] C. Woodford. "Lithium-ion batteries." Explain that Stuff. <https://www.explainthatstuff.com/how-lithium-ion-batteries-work.html> (accessed Nov. 23, 2025).
- [97] Epec, LLC. "Primary and Rechargeable Battery Chemistries with Energy Density." Epec Technical Resources. <https://www.epectec.com/batteries/chemistry/> (accessed Nov. 23, 2025).
- [98] DigiKey Electronics. "A Designer's Guide to Lithium Ion (Li-ion) Battery Charging." DigiKey. <https://www.digikey.com/en/articles/a-designer-guide-fast-lithium-ion-battery-charging> (accessed Nov. 23, 2025).
- [99] J. Xing. "Mastering the Art of Lithium Battery Charging." Lithium Battery Tech. <https://www.lithiumbatterytech.com/mastering-the-art-of-lithium-battery-charging/> (accessed Nov. 23, 2025).
- [100] Ufine Battery. "Everything You Need to Know About the 14500 Lithium Battery." Ufine Battery Blog. <https://www.ufinebattery.com/blog/everything-you-need-to-know-about-the-14500-lithium-battery/> (accessed Nov. 23, 2025).
- [101] INR18650. "14500 vs 18650: Comparative Analysis Lithium Battery." INR18650 Blog. <https://www.inr18650.com/blog/14500-vs-18650-comparative-analysis-lithium-battery.html> (accessed Nov. 23, 2025).
- [102] Redway Battery. "What Battery Can Replace an 18650? Comparing 21700 and 14500 Alternatives." Redway Battery. <https://www.redwaybattery.com/what-battery-can-i-use-instead-of-18650-exploring-the-21700-and-14500-alternatives/> (accessed Nov. 23, 2025).

- [103] Battle Born Batteries. "Pouch vs. Prismatic vs. Cylindrical? Your Lithium Battery Cell Guide." Battle Born Batteries.
<https://battlebornbatteries.com/pouch-vs-prismatic-vs-cylindrical-lithium-battery-cells/> (accessed Nov. 23, 2025).
- [104] Redway Battery. "What Battery Can Replace an 18650? Comparing 21700 and 14500 Alternatives." Redway Battery.
<https://www.redwaybattery.com/what-battery-can-i-use-instead-of-18650-exploring-the-21700-and-14500-alternatives/> (accessed Nov. 23, 2025).
- [105] Ufine Battery. "Everything You Should Know About 18650 Battery Voltage." Ufine Battery Blog.
<https://www.ufinebattery.com/blog/everything-you-should-know-about-18650-battery-voltage/> (accessed Nov. 23, 2025).
- [106] Saphiion. "Everything You Need to Know About Lithium-Ion 21700 Battery." Saphiion Blog.
<https://saphiion.com/blog/everything-you-need-to-know-about-lithium-ion-21700-battery/> (accessed Nov. 23, 2025).
- [107] Nuranu Battery. "21700 Battery vs 18650 Battery: Which Is Better for Power and Runtime?" Nuranu Battery.
<https://nuranubattery.com/21700-battery-vs-18650-battery/> (accessed Nov. 23, 2025).
- [108] D. Goodwin. "Power Supplies: Understanding the Differences Between Linear and Switching." Control Automation.
<https://control.com/technical-articles/power-supplies-understanding-the-differences-between-linear-and-switching/> (accessed Nov. 23, 2025).
- [109] W. Whitesell. "What Is the Function of the Power Supply Unit." Robots.net.
<https://robots.net/tech/what-is-the-function-of-the-power-supply-unit/> (accessed Nov. 23, 2025).
- [110] Electrical Academia. "Power Supply: Definition, Functions & Components." Electrical Academia.
<https://electricalacademia.com/electronics/power-supply-definition-functions-components/> (accessed Nov. 23, 2025).
- [111] P. Kumar. "How to Achieve Galvanic Isolation for Electrical Safety." Electronics Guruji.
<https://electronicsguruji.com/galvanic-isolation-and-electrical-safety/> (accessed Nov. 23, 2025).
- [112] Cadence PCB Solutions. "Linear Power Supply vs. Switching Power Supply: Advantages and Disadvantages." Cadence Resources.
<https://resources.pcb.cadence.com/blog/2020-linear-power-supply-vs-switching-power-supply-advantages-and-disadvantages> (accessed Nov. 23, 2025).
- [113] B. Griffith. "Linear vs. Switching Power Supplies." Keysight Blogs.
<https://www.keysight.com/blogs/en/tech/bench/2018/09/28/linear-vs-switching-power-supplies> (accessed Nov. 23, 2025).
- [114] Rohde & Schwarz. "Optimizing EMI Input Filters for Switched Mode Power Supplies." Application Note, Aug. 27, 2021.
<https://www.rohde-schwarz.com/us/applications/optimizing-emi-input-f> (accessed Nov. 23, 2025).

- [115] R. Severns, "Design of Snubbers for Power Circuits," Cornell Dubilier Electronics, Technical Paper, 2006. [Online]. Available: <https://www.cde.com/resources/technical-papers/design.pdf>.
- [116] D. Krambeck. "An Introduction to Rectifier Circuits." All About Circuits. <https://www.allaboutcircuits.com/technical-articles/an-introduction-to-rectifier-circuits/> (accessed Nov. 23, 2025).
- [117] R. Teja. "Low Drop Out Regulator (LDO Voltage Regulator)." Electronics Hub, Sep. 16, 2024. <https://www.electronicshub.org/ldo-low-drop-out-regulator/> (accessed Nov. 23, 2025).
- [118] Microchip Technology Inc., "EMI, EMC, EFT, and ESD Circuit Design Considerations for 32-bit Microcontrollers," Application Note AN2587, 2017. [Online]. Available: <https://ww1.microchip.com/downloads/aemDocuments/documents/OTH/ApplicationNotes/ApplicationNotes/00002587A.pdf>.
- [119] U.S. Department of Energy, "10 CFR Part 430 – Energy Conservation Program for Consumer Products," Electronic Code of Federal Regulations, §430.32(z), Oct. 15, 2025. [Online]. Available: [https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-430#p-430.32\(z\)](https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-430#p-430.32(z))
- [120] M. R. Fernández, E. Z. Casanova, and I. G. Alonso, "Review of display technologies focusing on power consumption," MDPI, https://www.researchgate.net/publication/282219145_Review_of_Display_Technologies_Focusing_on_Power_Consumption (accessed Oct. 28, 2025).
- [121] A. Mohammad Bagher, "Comparison of LED and OLED," SAS Publishers, <https://saspublishers.com/media/articles/SJET44206-210.pdf> (accessed Oct. 28, 2025).
- [122] S. Kim and H. Yoo, "Active-matrix array based on thin-film transistors using emerging materials for application: From lab to industry," MDPI, <https://www.mdpi.com/2079-9292/13/1/241> (accessed Oct. 28, 2025).
- [123] "Understanding Crosstalk in Display Technology: Causes and Control," China lcd display manufacturers, <https://lcddisplay.co/crosstalk-in-display-technology/a-Tyler> (accessed Oct. 28, 2025).
- [124] H.-W. Chen, J.-H. Lee, B.-Y. Lin, S. Chen, and S.-T. Wu, "Liquid crystal display and organic light-emitting diode display: Present status and future perspectives," Light, science & applications, <https://pmc.ncbi.nlm.nih.gov/articles/PMC6060049> (accessed Oct. 30, 2025).
- [125] L. E. Shan, M. Zeedhan, M. H. Baswaid, and N. U. Amin, "IOT-based Heart Rate Monitoring: A comparative analysis of microcontroller systems for real-time health monitoring," Preprints.org, <https://www.preprints.org/manuscript/202503.0968/v1> (accessed Oct. 4, 2025).
- [126] S. Gupte, P. A. Kadam, and R. Gupte, "Evaluating Microcontrollers for Embedded and IoT Applications: Criteria, Trade-offs, and Selection Framework," Evaluating microcontrollers for embedded and IOT applications: Criteria,

- trade-offs, and selection framework,
<https://www.ijraset.com/research-paper/microcontrollers-for-embedded-and-iot-applications> (accessed Oct. 5, 2025).
- [127] M. Zibayiwa, “A review on the inter-processor communication: I2C, UART, and SPI interfacing techniques,” ResearchGate, https://www.researchgate.net/publication/356556000_A_Review_on_The_Inter-Processor_Communication_I2C_UART_and_SPI_interfacing_techniques (accessed Nov. 23, 2025).
- [128] ACL Digital, “RTOS or bare-metal: A technical comparison for embedded system design,” ACL Digital, <https://www.acldigital.com/blogs/rtos-vs-bare-metal-embedded-architecture> (accessed Oct. 29, 2025).
- [129] EMMA International, “Common software languages for medical devices,” EMMA International, <https://emmainternational.com/common-software-languages-for-medical-devices> (accessed Oct. 29, 2025).
- [130] J. He, “Ti,” Application Report, <https://www.ti.com/lit/an/slaae25/slaae25.pdf?ts=1650452743573> (accessed Oct. 30, 2025).
- [131] 3fo, “IEC software standards,” Parasoft, <https://www.parasoft.com/blog/what-is-iec-62304-how-is-it-used-in-medical-device-compliance/> (accessed Nov. 25, 2025).
- [132] Simbex, “Mastering IEC 60601 compliance: Essential safety standards for medical devices,” Simbex, <https://simbex.com/mastering-iec-60601-compliance-essential-safety-standards-for-medical-devices/#:~:text=Brief%20History%20and%20Origins,requirements%20for%20medical%20electrical%20equipment.> (accessed Nov. 25, 2025).

APPENDIX B - AI PROMPT EXAMPLES

B.1 ETHAN'S EXAMPLES

B.1.1 Research Reports Generated by Gemini

B.1.1.1 Successful Prompt

“Provide an engineering level document describing the form and function of a reflective dual-wavelength PPG sensor. Include general hardware requirements and costs. Provide information regarding the use cases and capability limitations. Explain the theory behind the measurements and the requirements for taking measurements/processing signals. Explain the necessary things needed to implement this sensor on a PCB.”

B.1.1.2 Successful Response

Engineering-Level Document: Form and Function of a Reflective Dual-Wavelength Photoplethysmography Sensor

1. Foundational Principles and Biophysics of Reflective Photoplethysmography

1.1. Introduction to Photoplethysmography (PPG) and Its Historical Context

Photoplethysmography is a non-invasive optical technique used to detect blood volume changes in the microvascular bed of tissues.¹ The technology's foundational principle is that hemoglobin, the oxygen-carrying protein in blood, selectively absorbs light. This absorption varies

dynamically with the volume of blood passing through the tissue, a phenomenon that is synchronized with each cardiac cycle.³ By measuring these fluctuations in absorbed light, a PPG sensor can derive a pulsatile waveform rich with physiological information.⁵

The concept originated in the 1930s with Alrick Herzman's "photoelectric plethysmography," which was based on the principle of light absorption by transilluminated tissue.⁵ Herzman's early work demonstrated a clear correlation between blood volume changes and his optical measurements, validating the method against mechanical plethysmography.⁵ The technology has since evolved from its original transmission-mode configuration, where the light source and detector are placed on opposite sides of a body part (e.g., a finger clip), to the more versatile reflectance mode.⁴ In a reflective setup, the light source and detector are positioned on the same side of the tissue, enabling a much broader range of applications and body locations for measurement, such as the wrist, forehead, or earlobe.⁵

1.2. The Modified Beer-Lambert Law: The Guiding Principle

The theoretical underpinning of PPG is the Beer-Lambert Law, which describes the exponential attenuation of light as it passes through an absorbing medium.¹⁰ The law posits that light intensity decreases exponentially based on the attenuation coefficient of the material, the path length the light travels through it, and the concentration of absorbing and scattering particles.³ This principle is applied to PPG in a modified form to account for the complexities of light interaction with human tissue.¹⁰

The modification of the law is not a mere theoretical adjustment; it is a critical conceptual pivot that enables the functional application of PPG to non-invasive biometrics. The raw optical signal detected by a PPG sensor is a composite signal with two primary components: a large, stable Direct Current (DC) component and a small, pulsatile Alternating Current (AC) component.¹ The DC component represents the baseline light absorption by non-pulsatile components, such as skin, bone, and venous blood, whose volume and optical properties do not change significantly with the cardiac cycle.³ The AC component, typically less than one percent of the DC signal, is the crucial, time-varying signal caused by the dynamic changes in arterial blood volume with each heartbeat.¹ Because the PPG sensor's objective is to measure these small dynamic changes, it must focus on the relative changes in light intensity rather than the absolute intensity. This is what the modified law allows. The system essentially performs a continuous automatic zero calibration, constantly adjusting its baseline to track the relative changes that matter for heart rate and oxygen saturation. This approach makes PPG sensors highly adaptable to varying skin tones and ambient light conditions, a fundamental requirement for reliable wearable technology.⁶

1.3. Wavelength-Dependent Light Penetration and Hemoglobin Absorption

The effectiveness of a dual-wavelength PPG sensor hinges on the strategic selection of light

wavelengths and their distinct interactions with human tissue and blood.¹ Different wavelengths of light penetrate the skin to different depths. For instance, shorter wavelengths like blue and green are strongly absorbed by melanin and only penetrate to the superficial capillary beds in the subepidermal and dermal layers.¹ In contrast, longer wavelengths, specifically red light (around 660 nm) and infrared (IR) light (around 940 nm), penetrate much deeper, reaching the arteries and arterioles in the subcutaneous tissue.¹ This depth-dependent penetration is a key principle of multi-wavelength PPG, enabling the system to isolate and study specific vascular layers.¹

The selection of red and IR light is particularly important because of the distinct absorption characteristics of oxygenated hemoglobin (HbO₂) and deoxygenated hemoglobin (Hb) at these wavelengths.¹⁷

HbO₂ absorbs more IR light and less red light, while Hb absorbs more red light and less IR light.¹⁷ This differential absorption is the central biophysical basis for pulse oximetry. The high-contrast signals generated by these specific wavelengths enable the algorithms to differentiate between the two forms of hemoglobin and, by extension, calculate blood oxygen saturation.¹⁸ This is in stark contrast to green light, which, while excellent for heart rate monitoring due to its strong absorption in superficial capillaries, is not suitable for SpO₂ measurement as it does not penetrate deep enough to assess the arterial blood required for the calculation.¹ The choice of these wavelengths is therefore not arbitrary; it is a direct consequence of the physics of light-hemoglobin interaction.

Table 1: Key Biophysical Properties of PPG Wavelengths

Wavelength	Wavelength Range (nm)	Primary Absorbing Chromophores	Typical Penetration Depth	Primary Application
Green	510-550	Melanin, Hemoglobin	Superficial Capillary Bed	Heart Rate (HR)
Red	650-670	Deoxyhemoglobin in (Hb)	Deep Dermis, Arteries	Pulse Oximetry (SpO ₂)
Infrared (IR)	900-950	Oxygenated Hemoglobin (HbO ₂)	Subcutaneous Arteries	Pulse Oximetry (SpO ₂)

2. The Reflective Dual-Wavelength Sensor: Form and Function

This section delves into the physical architecture of the sensor, detailing its components and the core method for calculating blood oxygen saturation.

2.1. System Architecture: A Functional Block Diagram

A modern PPG sensor is best understood as a complete optoelectronic system.⁷ The system begins with a light source, typically a pair of Light Emitting Diodes (LEDs) for red and infrared light. These LEDs illuminate the tissue, and a nearby photodetector (PD) captures the reflected light.² The photodetector's output, a weak analog current signal, is then conditioned and digitized by a specialized integrated circuit known as an Analog Front-End (AFE).¹² The digitized signal is finally processed by a microcontroller (MCU), which runs the algorithms to extract vital signs like heart rate and oxygen saturation.² This overall architecture shows how the components form a cohesive signal chain, from optical input to digital output.²

2.2. Core Hardware Components and Their Interplay

The two essential components of a reflective dual-wavelength sensor are the light sources and the photodetector.⁷ For SpO₂ measurement, the light sources are a red LED (approx. 660 nm) and an infrared LED (approx. 940 nm).⁸ The LEDs are pulsed sequentially, allowing the photodetector to capture the absorption characteristics of each wavelength independently, preventing signal corruption.¹⁸ The photodetector, typically a photodiode, converts the received light back into a weak electrical current, often in the nano-ampere range.⁸ In a reflective setup, the light travels an arc-shaped or "banana-shaped" path through the tissue, scattering as it interacts with various layers before being captured by the detector on the same side.³

The engineering challenge of this system is to manage the minuscule signal from the photodiode in a robust and efficient manner. This is where the modern trend toward high integration becomes so crucial. While a system can be built from discrete components—separate LEDs, a photodiode, and a custom analog circuit using op-amps, filters, and ADCs—the industry has largely moved to integrated solutions from manufacturers like Texas Instruments and Analog Devices.²¹ These specialized integrated circuits (e.g., TI's AFE4403/4950 or Maxim's MAX30102) combine the LED drivers, photodetector, Transimpedance Amplifier (TIA), ambient light cancellation, and high-resolution ADC into a single, compact package.²¹ This high level of integration simplifies the PCB design, significantly reduces the physical footprint, and minimizes cost and complexity for manufacturers.²¹ More importantly, it dramatically improves performance by reducing electrical noise and crosstalk, which are critical issues when dealing with signals in the nano-ampere range.²¹ This integration is a direct engineering response to the fundamental signal-to-noise ratio problems inherent in PPG and allows for robust performance in challenging conditions, such as on the wrist, where the pulsatile signal is inherently weak.²¹

2.3. The SpO2 Measurement Principle: The Ratio of Ratios Method

The standard algorithmic method for calculating blood oxygen saturation (SpO2) is the "ratio of ratios".⁸ The process involves several key steps. First, the algorithm separates the raw signal for each wavelength into its AC and DC components.⁸ The AC component represents the pulsatile arterial blood, while the DC component represents the constant absorption from other tissues and non-pulsatile blood.⁸ The ratio of the AC to DC component, known as the modulation ratio, is then calculated for both the red and infrared signals.⁸ A higher modulation ratio indicates a stronger pulsatile signal and greater arterial absorption.¹⁸

The final step is to compute the R-value, or "ratio of ratios," which is a ratio of the red modulation ratio to the infrared modulation ratio.⁸ This R-value is negatively correlated with SpO2.¹³ The final

SpO2 percentage is not derived from a universal physical constant but from an empirically derived calibration curve. Many manufacturers use a linear model for this calculation, such as the formula provided by Texas Instruments: $SpO2 = 110 - 25 \times R$.⁸ It is crucial to note that this is a general model, and accurate

SpO2 measurements require device-specific calibration, which involves collecting data from test subjects in a controlled lab environment and against a reference device.¹³

Table 2: Estimated Bill of Materials (BOM) for a Dual-Wavelength PPG Sensor

Component	Description	Estimated Cost Range (USD)
Integrated IC/Module (Option 1)		
Sensor IC (e.g., MAX30102, AFE4950)	Integrated LEDs, PD, AFE	\$10-\$25
Microcontroller (MCU)	Low-power ARM Cortex-M0/4	\$2-\$10
Discrete Components (Option 2)		
Red LED (660 nm)	High-brightness, low-power	\$1-\$5

Infrared LED (940 nm)	High-brightness, low-power	\$1-\$5
Photodiode (PD)	Broad spectral sensitivity	\$5-\$10
Analog Front-End (AFE)	Op-amps, ADC, filters	\$10-\$30
Total Estimated Cost		
Integrated Approach		\$12-\$35
Discrete Approach		\$17-\$50
Note: Costs are approximations and can vary significantly based on quantity, manufacturer, and specific component choices.		

3. Hardware Implementation and System-Level Design

3.1. Analog Front-End (AFE) Architecture

The Analog Front-End is the critical interface between the analog world of the photodiode and the digital world of the microcontroller. It is responsible for converting the weak photodiode current into a high-quality digital signal.¹²

The first stage of the AFE is the Transimpedance Amplifier (TIA).¹² This circuit converts the photodiode's nano-ampere current into a measurable voltage. The TIA must be low-noise and have a high gain to amplify the tiny AC component of the PPG signal without introducing additional noise.¹² The next crucial stage is DC offset cancellation. The large DC component, which can be thousands of times stronger than the AC signal, can easily saturate the TIA and subsequent ADC, rendering the sensor useless.¹² Modern integrated AFEs use an internal Digital-to-Analog Converter (DAC) to inject a reverse current that effectively nullifies the DC offset, ensuring that the full dynamic range of the amplifier and ADC is reserved for the small,

diagnostically important AC signal.²¹

Following the DC cancellation, the signal is fed into a Programmable Gain Amplifier (PGA) which can adjust the gain based on the signal strength, ensuring the signal is strong enough to be digitized accurately without saturating the ADC.⁸ Finally, a high-resolution ADC (typically 18-bit to 22-bit) converts the analog voltage into a digital code.²⁶ The high resolution is essential for capturing the minute fluctuations of the AC signal and ensuring a high-quality digital output for subsequent processing.

Table 3: Reflective Dual-Wavelength PPG System Block Diagram and Component Functions

Functional Block	Component(s)	Function
Light Source	Red & IR LEDs	Emit light pulses into the tissue.
Photodetection	Photodiode (PD)	Converts reflected optical signal to a weak analog current.
Signal Conditioning	Transimpedance Amplifier (TIA)	Converts PD current to voltage.
Noise Management	DC Cancellation Circuit	Removes large DC offset from non-pulsatile tissues.
Signal Amplification	Programmable Gain Amplifier (PGA)	Adjusts signal strength for optimal ADC performance.
Digitization	Analog-to-Digital Converter (ADC)	Converts analog voltage to a high-resolution digital signal.
Control & Processing	Microcontroller (MCU)	Controls AFE, processes digital data, runs algorithms, and manages power.
Output	Display, Wireless Module	Presents results to the user or transmits data to another device.

3.2. LED Driver and Timing Control

The LED driver circuitry is responsible for pulsing the red and IR LEDs with precise and stable current.²³ The sequential pulsing of the two LEDs is essential to obtain distinct measurements for each wavelength. The timing of these pulses, specifically the pulse frequency, is a critical parameter that affects both measurement accuracy and power consumption.²³ Research has shown that a higher frequency, such as 1400 Hz, can lead to more accurate SpO2 measurements compared to a lower frequency like 600 Hz.²³

This relationship between timing, performance, and power consumption is a central challenge in wearable device design. Increasing the LED current or extending the pulse width provides more incident light, which in turn improves the overall signal strength and the signal-to-noise ratio (SNR).⁸ A higher SNR is necessary for accurate SpO2 measurement.³² However, this comes at a direct cost to battery life. An expert-level design must intelligently navigate this trade-off. Modern solutions address this problem through advanced timing controls, such as burst mode operation.²⁴ This allows the system to remain in a low-power state with minimal or no pulsing during periods of inactivity and to dynamically ramp up LED intensity and sampling rate in response to detected motion or during periods of on-demand measurement.³¹ This dynamic approach ensures that the device provides the required accuracy while maximizing battery life, demonstrating a sophisticated, system-level design philosophy.

3.3. Microcontroller (MCU) and Power Management

The MCU serves as the central processing unit, orchestrating the entire system.² It communicates with the AFE via a standard digital interface like I2C or SPI, retrieving the high-resolution digital data.²⁶ The MCU then runs the complex algorithms necessary for signal processing, vital sign extraction, and motion artifact removal.³¹ For battery-powered wearable applications, selecting a low-power MCU with sufficient processing capability is paramount to ensuring a long operational life.³⁰ Modern MCUs often include power management features, such as sleep modes, to further conserve energy.³⁰

4. Signal Processing and Algorithmic Requirements

4.1. Signal Preprocessing: The Essential First Step

The raw digital signals received from the AFE are not ready for analysis; they must first be preprocessed to remove unwanted noise and prepare them for algorithmic processing.³⁶ The first crucial step is filtering. A band-pass filter is applied to the raw signal to isolate the frequencies of interest, which typically correspond to the cardiac rhythm (between 0.5 Hz and 6.0 Hz).² This process removes low-frequency noise caused by respiration, thermoregulation, and other sources of baseline wander, as well as high-frequency noise from ambient light and electrical interference.¹⁴ After filtering, the red and IR signals are normalized to a common scale, a necessary step for consistent calculation of the R-value.¹⁸

4.2. Vital Sign Extraction Algorithms

Once the signal is preprocessed, various algorithms can be applied to extract vital signs. For heart rate (HR), the fundamental frequency of the pulsatile AC component is identified.³ This can be done using standard techniques like Fast Fourier Transform (FFT) or more advanced, high-precision methods like the MUSIC algorithm, which is well-suited for high-resolution frequency estimation from noisy signals.¹⁴ Heart Rate Variability (HRV) and Pulse Rate Variability (PRV), which provide insights into the autonomic nervous system, can also be derived from the timing of the inter-beat intervals of the PPG signal.⁵ For SpO₂ calculation, the algorithm takes the preprocessed red and IR signals, computes the AC/DC ratios, calculates the R-value, and then applies the device-specific empirical calibration curve to output the final oxygen saturation percentage.⁸

4.3. Motion Artifact (MA) Removal: The Persistent Challenge

The greatest challenge in real-world PPG monitoring is the presence of motion artifacts.³ Movement can introduce noise with an amplitude far exceeding that of the physiological signal and with frequencies that can overlap with the heart rate, making simple filtering insufficient.¹⁴

The most common approach to address this issue is to use hardware-based solutions, primarily an integrated 3-axis accelerometer.⁵ The accelerometer provides a motion reference signal that is synchronized with the PPG data, allowing the system to identify periods of motion and either flag the data as unreliable or use it as an input for software-based correction algorithms.³¹

A synergistic relationship between hardware and software is essential for a robust solution. The accelerometer provides the context for when the signal is likely corrupted. This contextual information is then fed into sophisticated Digital Signal Processing (DSP) algorithms. For example, adaptive filters (e.g., NLMS or RLS filters) can use the accelerometer data to generate a noise estimate and subtract it from the PPG signal, effectively canceling the motion artifact.¹⁴ Alternatively, Independent Component Analysis (ICA) can be used to separate the mixed signal into its statistically independent components, exploiting the fact that the physiological signal and the motion artifact are often uncorrelated.⁴¹ More recently, machine learning and deep learning models have emerged as a powerful approach, with algorithms like Convolutional Neural

Networks (CNNs) and Generative Adversarial Networks (GANs) learning to identify and reconstruct a clean PPG waveform from corrupted data.⁵ This multi-sensor, data-fusion approach is now considered the standard for achieving reliable performance in wearable devices.

Table 4: Key Signal Processing Techniques for PPG

Technique	Purpose	Key Inputs
Band-Pass Filtering	Noise reduction, signal isolation	PPG signal only
Adaptive Filtering (e.g., NLMS, RLS)	Motion artifact removal	PPG + Accelerometer data
Independent Component Analysis (ICA)	Signal separation	PPG signal only
Fast Fourier Transform (FFT)	Heart rate frequency estimation	Filtered PPG signal
Machine Learning (e.g., CNN, GAN)	Signal reconstruction, motion artifact removal	PPG + Accelerometer (optional)

5. PCB Design and Mechanical Considerations

5.1. PCB Layout Strategies for Noise Reduction

Even with the best components, a poor PCB layout can severely degrade a PPG sensor's performance.⁴² The weak, sensitive nature of the analog PPG signal makes it highly susceptible to electrical interference. Therefore, a meticulous PCB design is essential.

Proper grounding is paramount. Implementing a solid ground plane beneath the sensor and analog components provides a low-impedance path for return currents and acts as a shield against electromagnetic interference (EMI) and crosstalk.⁴² For multi-layer PCBs, dedicating one internal layer to ground is a common and effective strategy.⁴² Furthermore, it is critical to separate the

analog and digital ground planes and connect them at a single point, a technique known as star grounding. This prevents noisy digital currents from contaminating the sensitive analog circuitry and creating ground loops, which are a major source of noise.⁴²

Component placement is another key consideration. Sensitive analog components, such as the photodetector and AFE, should be placed as far as possible from high-speed digital components like the microcontroller and its associated clock and data traces.¹⁶ A distance of 10-15 mm is recommended to prevent noise coupling.⁴² All signal traces, especially analog lines, should be kept as short as possible and routed away from high-speed digital lines.⁴² The use of decoupling capacitors (e.g., 0.1 μ F and 1 μ F) placed as close as possible to the power pins of each integrated circuit is also critical for ensuring a clean and stable power supply.⁴²

5.2. Mechanical Design and Sensor-Skin Interface

The physical interface between the sensor and the user's skin is a fundamental factor in a PPG system's accuracy, just as important as the electronics.¹⁴ For a reflective sensor, the physical contact must be consistent and firm to ensure proper optical coupling and to minimize the impact of motion artifacts and ambient light interference.¹⁴

However, this creates a delicate trade-off, often referred to as the "Goldilocks" pressure problem. If the sensor is too loose, ambient light can contaminate the signal, and even slight movements can cause large-amplitude motion artifacts that corrupt the readings.⁵ Conversely, if the sensor is pressed too tightly against the skin, it can occlude the arteries and suppress the pulsatile blood flow, which dramatically reduces the AC signal amplitude and can result in a flat, unusable waveform.⁵ The optimal pressure is a narrow range, typically a few mmHg, that provides a snug fit without impeding blood flow.¹⁴ The final product's performance is thus not only a function of the PCB design and component selection but also of the mechanical design of the enclosure and strap, which must maintain this optimal, consistent pressure in a comfortable manner for the user.

6. Use Cases, Limitations, and Performance Analysis

6.1. Applications and Use Cases

PPG technology has become a cornerstone of both clinical and consumer health monitoring. In a clinical context, PPG sensors are used for continuous vital sign monitoring in hospitals and for diagnostic procedures like the Toe Brachial Index (TBI), a test for peripheral vascular disease.¹⁵ They are also used for assessing autonomic nerve function and for detecting a variety of cardiovascular conditions.¹² In the consumer and wellness sector, PPG sensors are a standard

feature in smartwatches and fitness trackers, providing continuous heart rate, heart rate variability (HRV), and SpO2 monitoring.⁶ These applications enable users to track fitness activities, monitor sleep quality, and gain personalized health insights.⁶

6.2. Capability Limitations and Environmental Factors

Despite their versatility, PPG sensors have several significant limitations that must be accounted for in design and application. The most challenging limitation is the susceptibility to motion artifacts, particularly in devices worn on the wrist.³ As discussed, these artifacts can easily overwhelm the physiological signal. Another major limitation is the influence of skin pigmentation and tattoos.¹⁵ Melanin absorbs light, which can attenuate the signal and lead to a systematic overestimation of SpO2 in individuals with darker skin tones, especially at low oxygen saturation levels.⁴⁴ This bias has led to criticism of consumer devices and has spurred manufacturers to develop software-based correction algorithms and increase LED intensity to compensate.⁴⁴ Ambient light is a persistent noise source, though modern integrated AFEs often include dedicated ambient light cancellation features to mitigate this.⁶ Finally, low blood perfusion, such as in cold extremities, can lead to a very weak pulsatile signal, making it difficult or impossible to obtain a reliable reading.²¹

6.3. Performance Metrics and Benchmarks

To quantify the performance of a PPG sensor, several key metrics are used. Signal-to-Noise Ratio (SNR) is the ratio of the power of the desired physiological signal to the noise power.³¹ A high SNR is paramount for accuracy. For basic heart rate monitoring, an SNR > 15 dB is generally considered sufficient, while accurate SpO2 measurement requires an SNR of 30 dB or higher.³¹ The Mean Absolute Error (MAE) is the average difference between the sensor's reading and a gold standard reference device, such as an electrocardiogram (ECG) for heart rate or a clinical-grade pulse oximeter for SpO2.³¹ The Perfusion Index (PI), defined as the ratio of the AC to DC signal, indicates the strength of the pulsatile blood flow at the measurement site.⁸ A PI of at least 0.2% is required for a reliable SpO2 reading.³¹

Table 5: PPG Sensor Performance Metrics and Benchmarks

Metric	Definition	Benchmark for HR	Benchmark for SpO2
Signal-to-Noise Ratio (SNR)	Ratio of signal power to noise power.	> 15 dB	> 30 dB

Mean Absolute Error (MAE)	Average error vs. a reference device.	< 5 BPM for HR	Varies by application/standard
Perfusion Index (PI)	Ratio of AC/DC signal amplitude.	N/A	> 0.2%

7. General Hardware Costs and Market Trends

The cost of building a PPG sensor system has decreased dramatically due to advances in sensor technology and high integration.⁴⁶ Integrated sensor modules like the Maxim MAX30102, which include LEDs, photodiodes, and a complete AFE, are available for as low as \$12 to \$22 in single-unit quantities.³⁵ Standalone AFEs like the TI AFE4403 are also cost-effective at around \$7 to \$10.⁴⁹ The total cost of the sensing components for a consumer-grade device, excluding the main processor and enclosure, is often under \$20.⁴⁶

There is a significant distinction between consumer and medical-grade devices.⁴ While the core technology is similar, medical-grade pulse oximeters from companies like Masimo can cost hundreds or thousands of dollars.⁵⁰ This high cost is primarily due to the stringent regulatory requirements, rigorous clinical validation, and liability associated with medical device certification.⁴ Consumer devices, while increasingly accurate, are sold for "wellness" and "fitness" purposes and do not carry a medical certification.⁴⁷

The low cost and high integration of modern PPG solutions are democratizing access to physiological monitoring. This technology is no longer confined to expensive clinical settings; it is now a standard feature in ubiquitous consumer electronics, making biometric data accessible to a wider population.⁴⁶ This market trend has had a ripple effect, driving innovation in software algorithms and leading to new research in areas like home health monitoring, sleep tracking, and personalized wellness. The relatively low barrier to entry for a functional prototype, with some modules costing as little as \$15, means that even hobbyists can now experiment with a technology once reserved for specialized medical instrument manufacturers.⁵²

8. Conclusion and Recommendations

A reflective dual-wavelength PPG sensor is a sophisticated optoelectronic system that leverages the biophysics of light-tissue interaction to non-invasively monitor vital signs. The successful implementation of such a sensor requires a holistic, engineering-level understanding of the entire signal chain, from the fundamental principles of the modified Beer-Lambert Law to the practical challenges of PCB layout and signal processing. The core of the technology relies on the

differential absorption of red and infrared light by oxygenated and deoxygenated hemoglobin, enabling the calculation of blood oxygen saturation via the "ratio of ratios" method.

For a successful implementation, it is highly recommended to use an integrated AFE solution. This approach addresses the most significant engineering challenges—noise management, power consumption, and miniaturization—in a single, high-performance component. A robust design must also incorporate an accelerometer for motion sensing, as motion artifacts remain the most significant source of error in real-world applications. The physical design of the sensor-skin interface is equally critical, requiring a careful balance to ensure proper contact without occluding blood flow. Finally, the system's performance must be evaluated against standard benchmarks, such as SNR and MAE, to ensure it meets the requirements of its intended application. The future of this technology will likely continue to be driven by advances in machine learning and sensor fusion, which will further improve accuracy and reliability in a wider range of dynamic, real-world conditions.

Works cited

1. Multi-wavelength photoplethysmography method for skin arterial ..., accessed September 19, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC5102532/>
2. Multi-Wavelength Photoplethysmography Device for the Measurement of Pulse Transit Time in the Skin Microvasculature - Computing in Cardiology, accessed September 19, 2025, <https://www.cinc.org/archives/2020/pdf/CinC2020-179.pdf>
3. An ML-Based Approach to Reconstruct Heart Rate from PPG in Presence of Motion Artifacts - PMC - PubMed Central, accessed September 19, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC10377343/>
4. wearable ppg sensors, accessed September 19, 2025, <https://pcardiowearables.com/product/wearable-ppg-sensor/>
5. sensors:ppg [SensorWiki.org], accessed September 19, 2025, <https://www.sensorwiki.org/sensors/ppg>
6. PPG Sensors: The Future of Safety Wearables and Heat Stress Management - SlateSafety, accessed September 19, 2025, <https://slatesafety.com/revolutionizing-workplace-safety-ppg-sensors/>
7. Basic principle of PPG sensors working in: (a) transmission, (b) reflection modes., accessed September 19, 2025, https://www.researchgate.net/figure/Basic-principle-of-PPG-sensors-working-in-a-transmission-b-reflection-modes_fig1_347589318
8. How to Design Peripheral Oxygen Saturation (SpO2) and Optical Heart Rate Monitoring (OHRM) Systems Using AFE4403 - Texas Instruments, accessed September 19, 2025, <https://www.ti.com/lit/pdf/slaa655>
9. Using Reflectometry for a PPG Waveform - Analog Devices, accessed September 19, 2025, <https://www.analog.com/en/resources/design-notes/using-reflectometry-for-a-ppg-waveform.html>
10. PPG Theory: Beer-Lambert Law #sleepscience #sleepresearch - YouTube, accessed September 19, 2025, <https://www.youtube.com/shorts/yM9VUwrGY34>
11. Beer-Lambert law along non-linear mean light pathways for the ..., accessed September 19, 2025, https://www.researchgate.net/publication/231151860_Beer-Lambert_law_along_no

[n-linear_mean_light_pathways_for_the_rational_analysis_of_Photoplethysmography](#)

12. Design of an Analog Front-End (AFE) for Photoplethysmography (PPG) Acquisition System - Advanced Sciences and Technology Journal, accessed September 19, 2025, https://astj.journals.ekb.eg/article_395349_76c9680b729346778b9d01ad4a095b40.pdf
13. Guidelines for SpO2 Measurement - Analog Devices, accessed September 19, 2025, <https://www.analog.com/en/resources/technical-articles/guidelines-for-spo2-measurement--maxim-integrated.html>
14. Current progress of photoplethysmography and SPO2 for health monitoring - PMC, accessed September 19, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC6431353/>
15. Photoplethysmography in Wearable Devices: A Comprehensive Review of Technological Advances, Current Challenges, and Future Directions - MDPI, accessed September 19, 2025, <https://www.mdpi.com/2079-9292/12/13/2923>
16. Investigating the Design of a Photoplethysmography Device for Vital ..., accessed September 19, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC11946623/>
17. Absorption spectra of oxygenated and deoxygenated hemoglobin between 400 nm and 630 nm (W.B. Gratzer, Med Res Council Labs, Holly Hill London and N. Kollias, Wellman Laboratories, Harvard Medical School, Boston). - ResearchGate, accessed September 19, 2025, https://www.researchgate.net/figure/Absorption-spectra-of-oxygenated-and-deoxygenated-hemoglobin-between-400-nm-and-630-nm_fig2_270050892
18. Calculating SpO2 using Photoplethysmography (PPG ... - Observable, accessed September 19, 2025, <https://observablehq.com/@roupenminassian/calculating-spo2>
19. observablehq.com, accessed September 19, 2025, <https://observablehq.com/@roupenminassian/calculating-spo2#:~:text=To%20calculate%20SpO2%20using%20PPG,differently%20at%20these%20two%20wavelengths.>
20. Respiratory Monitoring - An Introduction to Pulse Ox and Capnography - Taming the SRU, accessed September 19, 2025, <https://www.tamingthesru.com/blog/intern-diagnostics/how-does-this-pulse-ox-work>
21. Photoplethysmography (PPG) With Integrated AFE for Optical Biosensing - Texas Instruments, accessed September 19, 2025, <https://www.ti.com/lit/pdf/sbat014>
22. A low-power high-sensitivity analog front-end for PPG sensor, accessed September 19, 2025, <https://research.uaeu.ac.ae/en/publications/a-low-power-high-sensitivity-analog-front-end-for-ppg-sensor>
23. (PDF) Analysis of the Effect of Red LED and Infrared Flip Flop Frequency on SpO2 Measurement Accuracy - ResearchGate, accessed September 19, 2025, https://www.researchgate.net/publication/361047481_Analysis_of_the_Effect_of_Red_LED_and_Infrared_Flip_Flop_Frequency_on_SpO2_Measurement_Accuracy
24. Signal Conditioning IC for Proximity Sensors - Application Note 5375, accessed

- September 19, 2025, <https://docs.broadcom.com/docs/AV02-1031EN>
25. Design and Implementation of a Signal Conditioning Operational Amplifier for a Reflective Object Sensor - TRACE: Tennessee Research and Creative Exchange, accessed September 19, 2025, https://trace.tennessee.edu/cgi/viewcontent.cgi?article=1850&context=utk_gradthes
 26. AFE4403 data sheet, product information and support | TI.com, accessed September 19, 2025, <https://www.ti.com/product/AFE4403>
 27. MAX30102--High-Sensitivity Pulse Oximeter and ... - Analog Devices, accessed September 19, 2025, <https://www.analog.com/media/en/technical-documentation/data-sheets/max30102.pdf>
 28. MAX30102 Datasheet and Product Info - Analog Devices, accessed September 19, 2025, <https://www.analog.com/en/products/max30102.html>
 29. AFE4403 Ultra-Small, Integrated Analog Front-End for Heart Rate Monitors and Low-Cost Pulse Oximeters datasheet (Rev. C) - Texas Instruments, accessed September 19, 2025, <https://www.ti.com/lit/ds/sbas650b/sbas650b.pdf>
 30. Simplifying Wearable Tech: A Hobbyist's Guide to Creating a Basic Health Monitor PCB, accessed September 19, 2025, <https://www.allpcb.com/es-ES/blog/pcb-knowledge/simplifying-wearable-tech-a-hobbyists-guide-to-creating-a-basic-health-monitor-pcb.html>
 31. Maxim Integrated PPG Algorithms Specifications | Analog Devices, accessed September 19, 2025, <https://www.analog.com/en/resources/app-notes/maxim-integrated-ppg-algorithms-specifications.html>
 32. AC DC time Amplitude - Senbiosys, accessed September 19, 2025, <https://www.senbiosys.com/wp-content/uploads/2021/03/Every-photon-counts.pdf>
 33. How do pulse oximeters distinguish between arterial and venous blood to determine SpO2?, accessed September 19, 2025, <https://opencriticalcare.org/faq/how-do-pulse-oximeters-distinguish-between-arterial-and-venous-blood-to-determine-spo2/>
 34. What is the modulation ratio with regard to pulse oximetry? (R-Value) - Open Critical Care, accessed September 19, 2025, <https://opencriticalcare.org/faq/what-is-the-modulation-ratio-with-regard-to-pulse-oximetry-r-value/>
 35. MAX30102EFD+T | MAXIM | Price | In Stock | LCSC Electronics, accessed September 19, 2025, <https://www.lcsc.com/product-detail/C6454833.html>
 36. MUSIC-Based Algorithm for On-Demand Heart Rate Estimation ..., accessed September 19, 2025, <https://www.analog.com/en/resources/analog-dialogue/articles/music-based-algorithm-for-on-demand-heart-rate-estimation.html>
 37. www.analog.com, accessed September 19, 2025, [https://www.analog.com/en/resources/analog-dialogue/articles/music-based-algorithm-for-on-demand-heart-rate-estimation.html#:~:text=The%20periodicity%20of%20the%20PPG,%2C%20motion%20artifacts%20\(MA\).](https://www.analog.com/en/resources/analog-dialogue/articles/music-based-algorithm-for-on-demand-heart-rate-estimation.html#:~:text=The%20periodicity%20of%20the%20PPG,%2C%20motion%20artifacts%20(MA).)
 38. Motion Artifact Reduction for Wrist-Worn Photoplethysmograph Sensors Based on

- Different Wavelengths - MDPI, accessed September 19, 2025,
<https://www.mdpi.com/1424-8220/19/3/673>
39. Motion Artifact Removal Techniques for Wearable EEG and PPG Sensor Systems - Frontiers, accessed September 19, 2025,
<https://www.frontiersin.org/journals/electronics/articles/10.3389/felec.2021.685513/full>
 40. An Accurate Non-accelerometer-based PPG Motion Artifact Removal Technique using CycleGAN - NSF-PAR, accessed September 19, 2025,
<https://par.nsf.gov/servlets/purl/10359654>
 41. Motion Artifact Reduction in Photoplethysmography Using ..., accessed September 19, 2025,
https://www.researchgate.net/publication/3036431_Motion_Artifact_Reduction_in_Photoplethysmography_Using_Independent_Component_Analysis
 42. Optimizing Air Quality Monitoring PCB Design for Sensor ... - ALLPCB, accessed September 19, 2025,
<https://www.allpcb.com/ar-SA/blog/pcb-knowledge/optimizing-air-quality-monitoring-pcb-design-for-sensor-accuracy.html>
 43. Photo-plethysmography (PPG) Test with ABI Machines - Viasonix, accessed September 19, 2025,
<https://viasonix.com/vascular-angiology/photo-plethysmography-readings/>
 44. A Programmable Gain Calibration Method to Mitigate Skin Tone Bias in PPG Sensors - PMC, accessed September 19, 2025,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12293395/>
 45. Effect of skin tone and activity on the performance of wrist-worn optical beat-to-beat heart rate monitoring | Request PDF - ResearchGate, accessed September 19, 2025,
https://www.researchgate.net/publication/347544281_Effect_of_skin_tone_and_activity_on_the_performance_of_wrist-worn_optical_beat-to-beat_heart_rate_monitoring
 46. Healthcare Monitoring Using Low-Cost Sensors to Supplement and Replace Human Sensation: Does It Have Potential to Increase Independent Living and Prevent Disease? - PMC, accessed September 19, 2025,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC9963454/>
 47. Fermion: MAX30102 PPG Heart Rate & Oximeter Sensor (Breakout, I2C/UART) - RobotShop, accessed September 19, 2025,
<https://www.robotshop.com/products/fermion-max30102-ppg-heart-rate-oximeter-sensor-breakout-i2c-uart>
 48. Heart Rate Sensor Maxim Integrated MAX30102 | RAK12012 - RAKwireless Store, accessed September 19, 2025,
<https://store.rakwireless.com/products/wisblock-heart-rate-sensor-rak12012>
 49. AFE4403 | Buy TI Parts | TI.com, accessed September 19, 2025,
<https://www.ti.com/product/AFE4403/part-details/AFE4403YZPR>
 50. Ppg Sensor - eBay, accessed September 19, 2025,
https://www.ebay.com/shop/ppg-sensor?_nkw=ppg+sensor
 51. MAX86916EVSYS# ANALOG DEVICES, Evaluation Board, MAX86916, Integrated PPG & ECG Bio-Sensor Module | Newark Electronics, accessed

September 19, 2025,

<https://www.newark.com/analog-devices/max86916evsys/eval-board-ppg-ecg-bio-sensor/dp/65AH7985>

52. Gravity: PPG Heart Rate Monitor Sensor for Arduino (Analog/Digital) - DFRobot, accessed September 19, 2025, <https://www.dfrobot.com/product-1540.html>

B.1.1.3 Failed Prompt

Generate a research report assuming I already know the function and form of a dual wavelength (IR and Red) and a triple wavelength (IR, Red, and Green) PPG sensor that explains how adding a amber/yellow, blue, Extra NIR, or a Secondary NIR/Red impacts the capabilities of the sensor.

B.1.1.4 Failed Response

Advanced Spectroscopic Photoplethysmography: Functional Expansion Through Strategic Multi-Wavelength Architectures

1. Executive Summary: The Transition to N-Wavelength PPG Architectures

The utilization of Photoplethysmography (PPG) sensors has historically relied on dual-wavelength systems, primarily employing Red and Near-Infrared (NIR) light, a configuration established to facilitate the calculation of arterial oxygen saturation (SpO_2).¹ While robust for this foundational metric, the accuracy, generalizability, and capability of dual-wavelength sensing are highly sensitive to intrinsic biological characteristics, such as skin tone and sensor placement variability.³

The migration to triple-wavelength systems, typically incorporating Green light, provided an initial analytical advantage. Green light, due to its high absorption by hemoglobin, offers a less noisy, more robust signal for heart rate (HR) monitoring, and multi-wavelength processing techniques have proven effective in improving signal quality and handling motion artifacts.⁴ Furthermore, multi-wavelength approaches demonstrate superior performance in complex physiological estimations, such as cuffless blood pressure (BP) estimation, where the mean absolute difference was shown to decrease from 5.7 mmHg for single-wavelength PPG to a significantly improved 2.9 mmHg for three-wavelength PPG.⁶

However, achieving comprehensive non-invasive physiological assessment necessitates the expansion to N-wavelength architectures, where $N \geq 3$. The core challenge is the analytical requirement to decouple signal contributions from multiple chromophores that simultaneously influence light attenuation. If a system is tasked with measuring SpO_2 (two unknowns: Hb and HbO_2) plus a third non-pulsatile constituent, such as Bilirubin or glycated hemoglobin (HbA_1c)⁷, a minimum of three distinct wavelengths are required. If tissue scattering, melanin, or water content must also be quantified or compensated for, the system must expand to four or more wavelengths to ensure a mathematically solvable system of linear equations.

The addition of specific, strategically selected wavelengths fundamentally transforms the PPG platform from a simple cardiovascular rhythm monitor to a sophisticated tool for metabolic and deep tissue analysis. These enhancements enable the quantification of new chromophores (e.g., Bilirubin using Amber/Yellow), introduce depth-resolving capabilities (Blue for superficial vascularity, Extra NIR for deep tissue), and significantly enhance robustness against physiological noise sources (Secondary Red/NIR for skin tone compensation).⁸

2. Foundational Principles of Advanced Multi-Wavelength PPG Spectroscopy

2.1. Limitations of Standard Dual and Triple Configurations

The inherent physical interactions between light and tissue impose constraints on conventional PPG systems. Dual-wavelength systems are typically confined to SpO_2 measurement¹ and struggle with robustness across heterogeneous populations due to varying biological characteristics.³ Furthermore, extracting advanced metrics like Pulse Transit Time (PTT)—used for Pulse Wave Velocity (PWV) and cuffless BP estimation—requires high-fidelity, decoupled waveforms, often necessitating extraction of time delays from two distinct PPG waveforms or an external ECG.⁹

Triple-wavelength systems, while improved, still face limitations related to light penetration. Shorter wavelengths, such as Green light, exhibit limited penetration depth, restricting the acquisition of physiological data from deeper tissue layers where major arteries and tissue volume dynamics occur.⁵ Conversely, long-wavelength PPG in the NIR spectrum, while achieving deeper penetration, is often vulnerable to motion-induced noise.⁵ Achieving analytical generalizability requires overcoming these depth and noise limitations simultaneously, which mandates the use of spectrally distinct wavelengths to isolate specific components of the absorption spectrum.

2.2. Spectroscopic Basis for Wavelength Selection and Penetration

Light propagation through human tissue is governed by two key optical processes: absorption (μ_a) and scattering (μ_s).¹⁰ The chromophores primarily responsible for absorption include oxygenated hemoglobin (HbO_2), deoxyhemoglobin (Hb), tissue water (H_2O), and melanin.¹¹

PPG systems exploit the Near-Infrared (NIR) window (approximately 600 nm to 1000 nm), where absorption by water is minimal and hemoglobin dominates, maximizing tissue penetration.¹¹ A critical aspect of multi-wavelength PPG is the exploitation of the penetration depth gradient:

- Blue light exhibits the most superficial penetration, barely reaching 1 mm into the tissue.¹³
- Red light penetrates moderately, reaching approximately 4–5 mm beneath the skin surface.¹³
- Infrared (IR) light penetrates the deepest.⁴

This depth dependence allows N-wavelength systems to sample physiological information from different vascular beds, a technique utilized for depth-resolved PPG.⁸

2.3. The Analytical Imperative: N-Chromophore Decoupling via Matrix Algebra

The fundamental challenge in multi-wavelength PPG is isolating the pulsatile signal component (the ΔOD component) from the large baseline signal (OD_{DC}) and subsequently solving for the dynamic concentration changes (ΔC) of the chromophores. This analytical procedure relies on the Modified Beer-Lambert Law (MBLL).

The MBLL approximates the relationship between the change in optical density (ΔOD) measured by the sensor and the change in the tissue absorption coefficient ($\Delta \mu_a$) due to the arterial pulse, weighted by a differential path length factor (DPF):

The change in the absorption coefficient ($\Delta \mu_a$) at a given wavelength (λ) is modeled as the linear sum of the concentration changes of chromophores, weighted by their respective molar extinction coefficients (ϵ):

To accurately quantify unknown concentration changes (e.g., ΔC_{HbO_2} , ΔC_{Hb} , etc.), the system must employ at least spectrally distinct wavelengths (N). This generates a system of linear equations that can be expressed in matrix form:

In this equation, ΔOD is the vector of measured optical density changes at N wavelengths, E is the matrix containing the known molar extinction coefficients for each chromophore at each wavelength, and ΔC is the vector of unknown chromophore concentration changes.¹⁷

For instance, the dual-wavelength calculation is a simplification solving for ΔC_{HbO_2} and ΔC_{Hb} (a 2 system). The quantification of additional chromophores, such as Bilirubin, necessitates moving to a 3 or 4 system, solved via matrix inversion or least squares curve fitting.⁷ The expansion to four or more wavelengths is not merely an incremental improvement; it is an analytical prerequisite to obtain a well-conditioned matrix solution for these newly introduced unknown physiological parameters.

3. Wavelength Addition I: Amber/Yellow (570 nm – 620 nm)

3.1. Spectroscopic Rationale: Targeting Bilirubin and Intermediate Penetration

Amber/Yellow light, typically encompassing wavelengths between 570 nm and 620 nm, occupies a crucial segment of the visible spectrum. Its penetration depth is relatively shallow, ranging from 0.5 mm to 2 mm, which allows it to primarily interact within the epidermis and papillary dermis.¹⁹

The primary chromophore target for this wavelength band is bilirubin. Abnormal bilirubin metabolism is associated with various liver disorders, and its accumulation (hyperbilirubinemia) leads to jaundice, wherein bilirubin deposits cause a yellowish skin color.²¹ Crucially, the light attenuation in this band is sensitive to both hemoglobin and bilirubin.

The spectral position of Amber/Yellow light is designed to maximize the absorption contrast for bilirubin relative to other spectral inputs, allowing its concentration to be isolated from the highly dominant hemoglobin signal. The application of multi-wavelength PPG, combined with dynamic spectroscopy, enables the extraction of the blood absorption spectrum necessary to calculate the total bilirubin value non-invasively.²¹

3.2. Primary Capability Gain: Non-Invasive Bilirubin Measurement (TSB/TcB)

The introduction of the Amber/Yellow channel facilitates the development of non-invasive Total Serum Bilirubin (TSB) detection methods.²¹ This capability is highly significant in clinical practice, particularly in neonatology, as it offers a non-invasive, quick, and pain-free alternative to traditional invasive blood collection for bilirubin level detection.²¹ Neonatal jaundice affects over 80% of newborns, and continuous monitoring of bilirubin levels is essential to prevent kernicterus, a condition involving neurotoxicity and permanent neurological damage.²²

A highly accurate non-invasive bilirubin detection method utilizing multi-wavelength PPG has been validated, showing a strong correlation coefficient (r) compared to clinical-biochemical methods.²¹ This high degree of correlation confirms that the spectral information provided by the Amber/Yellow band, when processed within a multi-wavelength framework, successfully isolates the bilirubin component from background noise and other chromophores.

3.3. Secondary Benefits: Hematocrit and Skin Tone Mitigation

Beyond bilirubin, the Amber/Yellow wavelength provides complementary information valuable for other physiological estimates. Multi-wavelength systems operating under 1000 nm leverage scattering properties, particularly of Red Blood Cells (RBC), to estimate parameters like hematocrit (Hct) alongside and .²⁴ Because Amber/Yellow light penetrates to an intermediate depth and interacts strongly with blood, it offers a distinct spectral data point crucial for algorithms that model RBC scattering and concentration dynamics, thereby enhancing Hct estimation accuracy.²⁵

Furthermore, while shorter wavelengths are typically highly sensitive to melanin, the Amber/Yellow region provides an intermediate spectral profile between the visible Green light (high sensitivity) and the Red/NIR light (lower sensitivity). This intermediate data point contributes critical information to multi-wavelength models attempting to compensate for inter-subject variability arising from skin tone differences, improving the generalizability of the sensor across diverse skin complexions.³

Table 3.3.1: Amber/Yellow Wavelength Analysis (570-620 nm)
Feature

Primary Target Chromophore
Penetration Depth
Complexity Requirement
Secondary Contribution

4. Wavelength Addition II: Blue Light (400 nm – 480 nm)

4.1. Spectroscopic Rationale: Soret Band and Ultra-Superficial Sensing

The addition of a Blue light channel (e.g., 400 nm – 480 nm) introduces an optical component highly sensitive to hemoglobin dynamics. This spectral region includes the Soret band, where both oxy-hemoglobin (410 nm) and deoxy-hemoglobin (420 nm) exhibit their absolute maximum absorption coefficients.²⁶ This maximal absorption coefficient ensures that even minor changes in blood volume within the sampled tissue cause substantial modulations in the detected light intensity, providing maximum contrast for blood volume variations.

Conversely, the penetration depth of Blue light is severely limited, barely reaching 1 mm into the tissue.⁸ This ultra-superficial penetration depth restricts the signal largely to the capillary and sub-capillary plexus of the epidermis and upper dermis, where the blood volume changes are smaller but the light absorption contrast is exceptionally high.

4.2. Primary Capability Gain: Endothelial Function and Circulating Nitric Oxide (NO) Analysis

The interaction of blue light with the superficial vasculature offers unique diagnostic capabilities related to endothelial function. Blue light exposure, typically around 453 nm, has been demonstrated in clinical studies to improve endothelial cell (EC) function by increasing circulating nitric oxide (NO) species. These species are released from photolabile intracutaneous nitric oxide metabolites into the bloodstream upon irradiation.²⁷

This photochemical effect results in systemic cardiovascular benefits, including decreased systolic blood pressure, increased forearm blood flow, improved flow-mediated dilation (FMD), and reduced arterial stiffness (Pulse Wave Velocity, PWV).²⁸ A Blue PPG channel, due to its maximal sensitivity to superficial vascular responses, can be integrated into Photoplethysmography-Flow Mediated Dilation (PPG-FMD) measurement protocols. PPG-FMD provides a non-invasive, operator-independent method for measuring vascular health and endothelial function, offering a technical alternative to ultrasound-based FMD.²⁹ The ability of the Blue wavelength to actively influence and monitor the vascular system positions it as a key channel for preventative cardiovascular diagnostics.

4.3. Secondary Benefit: Motion Artifact Isolation and Superficial Blood Flow

A critically important analytical role for the Blue channel is as a high-fidelity reference for motion artifact rejection (MAR). In the presence of movement, the PPG signal () is a mixture of the true pulsatile signal () and noise arising from tissue displacement ().⁴

Since Blue light penetration is limited to the uppermost tissue layers (less than 1 mm), the

resulting signal is dominated by the displacement and scattering effects of the superficial skin layers, which constitute motion noise rather than deep arterial pulsatility. By obtaining this ultra-superficial signal using Blue light, the system can acquire a high-quality signal () proportional to skin motion.³⁰

This motion-dominated signal can then be fed into multi-channel decomposition algorithms, such as Independent Component Analysis (ICA) or Principal Component Analysis (PCA), to mathematically decouple the noise component from the true, deeper pulsatile signal acquired via Red/IR channels.⁴ Leveraging the Blue wavelength specifically for noise characterization enhances the overall robustness and accuracy of heart rate estimation in mobile, intensive motion situations.³⁰

5. Wavelength Addition III: Extra Near-Infrared (NIR) / Long-Wavelength NIR (>1000 nm)

5.1. Spectroscopic Rationale: The Second NIR Window and Water Absorption Dynamics

Standard pulse oximetry operates within the first Near-Infrared window (700 nm to 1000 nm), chosen because water absorption is minimized, and hemoglobin absorption dominates.¹¹ However, as the light wavelength extends beyond approximately 950 nm, the absorption coefficient of tissue water () begins to increase significantly.¹¹ This spectral region, sometimes extending up to 1100 nm, is known as the Second NIR Window.³⁴

Wavelengths in this long-NIR region (e.g., ⁸) maximize the depth of penetration, surpassing the capabilities of conventional Red and IR wavelengths, reaching structures relevant for deep tissue oximetry, such as bone and brain tissue.¹¹

5.2. Primary Capability Gain: Tissue Water Content and Deeper Tissue Oxygenation ()

The primary analytical advantage of an Extra NIR channel is the ability to quantify and compensate for tissue water content. Given the high concentration of in human tissue, its absorption must be explicitly accounted for if accurate quantification of other chromophores is required in the deeper tissue layers.¹¹

By introducing a wavelength where water absorption is prominent (i.e.,), the system gains the necessary spectral input to treat concentration as a third or fourth unknown variable in the MBL

matrix.³³ This spectral data point allows for non-invasive monitoring of tissue hydration status, which is highly relevant for diagnosing or tracking conditions involving edema or dehydration.

Furthermore, this wavelength region is integral to Near-Infrared Spectroscopy (NIRS), which monitors hemoglobin dynamics across multiple tissue layers for regional measurements.³⁴ This deep-penetrating light enables the estimation of tissue oxygen saturation (S_{tO_2}), a metric distinct from arterial S_aO_2 , as it reflects a combined saturation average typically weighted toward venous blood (approximately 80% venous and 20% arterial saturation).¹¹

5.3. Analytical Requirement: Water Compensation Mechanisms

In conventional NIRS or deep PPG systems operating around the 800 nm to 950 nm range, fluctuations in tissue water concentration—which vary due to physiological factors such as temperature, metabolism, or shock—introduce an uncontrolled variable that corrupts the concentration calculations for S_{tO_2} and S_aO_2 .¹⁰

Therefore, sophisticated multi-wavelength NIRS systems often employ a three-wavelength approach within the NIR spectrum to solve simultaneously for S_{tO_2} , S_aO_2 , and water concentration changes.³³ By selecting two standard NIR wavelengths (e.g., 780 nm, 850 nm) for hemoglobin contrast and adding a third, Extra NIR wavelength (e.g., 940 nm) highly sensitive to water, the system can apply a specific water-absorption correction algorithm based on solving the expanded MBL matrix.³³ The Extra NIR wavelength acts as a crucial internal correction factor, guaranteeing the reliability and fidelity of deep S_{tO_2} and hemodynamic measurements.

6. Wavelength Addition IV: Secondary NIR/Red for Calibration and Robustness

6.1. Rationale: Redundancy and Penetration Profile Matching

A secondary NIR or Red channel involves utilizing two distinct light sources within the Red or NIR spectrum (e.g., λ_{NIR1} and λ_{NIR2} NIR LEDs, or λ_{Red1} and λ_{Red2} Red LEDs). While these pairs maintain a similar deep penetration profile, their slightly varied spectral signatures allow for enhanced modeling of fixed, non-pulsatile optical absorbers and scatterers, such as melanin and generalized tissue scattering.⁸

This spectral redundancy provides an increased dimensionality in the measurement data, which is essential for decoupling the concentration dynamics of pulsatile blood from baseline interference.

6.2. Primary Capability Gain: Biometric Normalization (Skin Tone Compensation)

Skin pigmentation, determined by melanin concentration, is a significant non-arterial source of variability and signal attenuation in PPG measurements, especially in individuals with darker skin tones.³⁶ Melanin strongly absorbs light in the visible and shorter NIR range, severely reducing the signal-to-noise ratio (SNR) and compromising the accuracy of and measurements.³⁷

The implementation of a secondary Red or NIR channel enables a proactive calibration strategy. By quantifying the degree of light absorption at a wavelength known to be highly affected by melanin (e.g., to), the system can establish a baseline metric for the user's skin pigmentation level at the point of contact. This quantification allows for the controlled application of gain adjustment (e.g., using a Programmable Gain Amplifier, PGA) during the initial setup.³⁷

This approach, validated experimentally, significantly improves signal consistency across diverse skin tones by normalizing the signal amplitude, effectively mitigating the effects of skin pigmentation without altering the native morphology of the PPG waveform. This pre-measurement gain correction is critical for ensuring reliable PPG sensing and generalizability in wearable devices designed for heterogeneous populations.³

6.3. Enhanced Signal Quality and Motion Artifact Reduction (MAR)

The use of multiple, highly distinct PPG channels (whether they vary by wavelength or sensor location) is the foundation for advanced digital signal processing techniques aimed at Motion Artifact Reduction (MAR).⁴

Algorithms such as Independent Component Analysis (ICA) or Principal Component Analysis (PCA) operate by decomposing the mixed, noisy multi-channel signals into statistically independent components, allowing the non-pulsatile components (motion and fixed scattering) to be identified and removed.⁴ Providing redundant spectral information through a Secondary NIR/Red channel enhances the spectral diversity available to the decomposition algorithm, thereby improving the statistical separation between the pure pulsatile signal and the motion artifact components. This results in superior performance and accuracy for heart rate estimation, even during vigorous activities such as fast walking or running.⁴

7. Synthesis, Trade-Offs, and System Design Implications

7.1. Comparative Impact of Advanced PPG Wavelengths

The strategic selection of wavelengths dictates the physiological capabilities of the N-wavelength sensor architecture. Each addition solves a specific problem related to either chromophore decoupling, noise separation, or depth resolution.

Table 7.1.1: Comparative Impact of Advanced PPG Wavelengths	
Wavelength Region	

Amber/Yellow (570-620 nm)	
Blue (400-480 nm)	
Extra NIR (>1000 nm)	
Secondary NIR/Red (e.g., 650 nm)	

7.2. System Design and Engineering Trade-offs

The transition from a basic dual-wavelength configuration to an N-wavelength spectroscopic device introduces significant engineering trade-offs.

Firstly, hardware complexity and cost increase proportionally. Each added wavelength requires a dedicated Light Emitting Diode (LED) driver channel and complex optical alignment to ensure proper source-detector separation (S-D gap). Custom four-wavelength devices, such as those employing Blue, Green, Yellow, and IR ⁶, necessitate highly integrated optical front-end (AFE) design.

Secondly, power consumption is a critical factor for wearable devices. Multi-wavelength systems must pulse multiple LEDs, either sequentially or concurrently, which results in substantially higher power consumption than single-channel monitors, posing a constraint on battery life and form factor.²

Finally, the data processing load intensifies dramatically. Simple dual-wavelength systems rely on fast, computationally inexpensive ratio-of-ratios methods. Conversely, N-wavelength architectures require solving systems of multi-dimensional linear equations (e.g., or matrices) using matrix inversion, least squares minimization, or regularized optimization techniques.¹⁷ This requires robust computational capacity within the embedded microcontroller unit (MCU) or reliance on external processing.

7.3. Conclusion: The Future of Spectroscopic Biomarker Monitoring

The analytical expansion of PPG sensors through the strategic addition of wavelengths such as Amber/Yellow, Blue, Extra NIR, and Secondary NIR/Red represents a fundamental shift in non-invasive physiological monitoring. This advancement is driven by the necessity of solving the generalized Modified Beer-Lambert Law matrix equation to quantify distinct chromophores simultaneously.

The integration of Amber/Yellow provides access to metabolic monitoring via non-invasive TSB detection, particularly valuable for neonatal care. Blue light, leveraging the Soret band and its shallow penetration, enables both active assessment of endothelial function and the creation of a high-fidelity noise reference channel crucial for motion artifact isolation. The incorporation of Extra NIR wavelengths addresses the critical need for compensating for tissue water fluctuations, thereby guaranteeing the accuracy of deep-tissue oxygen saturation (S_{tO_2}) measurements. Finally, the use of a Secondary NIR/Red channel facilitates proactive biometric normalization, providing the necessary redundancy for sophisticated statistical models (e.g., ICA/PCA) to maintain signal quality and consistency across diverse user populations and under challenging motion conditions.

Future advancements in PPG depend on the successful fusion of these advanced optical hardware designs with robust, spectral-domain signal processing techniques to realize a new generation of non-invasive monitors capable of measuring complex health biomarkers previously confined to laboratory analysis.

Works cited

1. Photoplethysmography for blood volumes and oxygenation changes during intermittent vascular occlusions - PMC, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC5943414/>
2. US11051706B1 - Multiple source-detector pair photoplethysmography (PPG) sensor - Google Patents, accessed October 8, 2025, <https://patents.google.com/patent/US11051706B1/en>
3. A Review of Wearable Multi-Wavelength Photoplethysmography - PubMed, accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/34669577/>
4. Motion Artifact Reduction in Wearable Photoplethysmography Based on Multi-Channel Sensors with Multiple Wavelengths - MDPI, accessed October 8, 2025, <https://www.mdpi.com/1424-8220/20/5/1493>
5. Photoplethysmography in Wearable Devices: A Comprehensive Review of

- Technological Advances, Current Challenges, and Future Directions - MDPI, accessed October 8, 2025, <https://www.mdpi.com/2079-9292/12/13/2923>
6. Please cite the Published Version (2021) A Review of ... - e-space, accessed October 8, 2025, https://e-space.mmu.ac.uk/628692/7/A_Review_of_Multi_Wavelength_Photoplethysmography_Accepted_Version%20e.pdf
 7. Quantitative Analysis of Different Multi-Wavelength PPG Devices and Methods for Noninvasive In-Vivo Estimation of Glycated Hemoglobin - MDPI, accessed October 8, 2025, <https://www.mdpi.com/2076-3417/11/15/6867>
 8. Multi-wavelength photoplethysmography for simultaneous recording of skin blood pulsations at different vascular depths - SPIE Digital Library, accessed October 8, 2025, <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/6430/1/Multi-wavelength-photoplethysmography-for-simultaneous-recording-of-skin-blood-pulsations/10.1117/12.724071.full>
 9. Sources of Inaccuracy in Photoplethysmography for Continuous Cardiovascular Monitoring - PMC - PubMed Central, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC8073123/>
 10. Quantification in tissue near-infrared spectroscopy - PMC, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC1691964/>
 11. Near-infrared window in biological tissue - Wikipedia, accessed October 8, 2025, https://en.wikipedia.org/wiki/Near-infrared_window_in_biological_tissue
 12. Absorption spectra for biological tissues - ECE 532, 3. Optical Properties, accessed October 8, 2025, <https://omlc.org/classroom/ece532/class3/muaspectra.html>
 13. Light penetration into skin illustrating the depth to which wavelengths... - ResearchGate, accessed October 8, 2025, https://www.researchgate.net/figure/Light-penetration-into-skin-illustrating-the-depth-to-which-wavelengths-penetrate-human_fig1_319652066
 14. Lightwave Therapy Principles, accessed October 8, 2025, <https://lightwavetherapy.com/learn/lightwave-therapy-principles/>
 15. Multi-wavelength photoplethysmography method for skin arterial pulse extraction - PubMed, accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/27867733/>
 16. PDE-constrained multispectral imaging of tissue chromophores with the equation of radiative transfer - PMC, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC3018054/>
 17. Resolving tissue chromophore concentration at MRI resolution using multi-wavelength photo-magnetic imaging - PMC, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC7449711/>
 18. How does Yellow Light help your skin? - Koanna, accessed October 8, 2025, <https://koanna.com/blogs/news/how-does-yellow-light-therapy-help-your-skin>
 19. How Yellow LED Light Therapy Can Help Heal Your Skin - TrueLight, accessed October 8, 2025, <https://www.shoptruelight.com/blogs/led-light-therapy-devices/yellow-light-therapy>
 20. Non-invasive detection of total bilirubin based on multi-wavelength ..., accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/37126889/>

21. Neonatal wearable device for colorimetry-based real-time detection of jaundice with simultaneous sensing of vitals, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC7929506/>
22. Development of Non-Invasive Biosensors for Neonatal Jaundice Detection: A Review, accessed October 8, 2025, <https://www.mdpi.com/2079-6374/14/5/254>
23. Multiple diagnosis based on Photo plethysmography : hematocrit, SpO2 , pulse and respiration - SPIE Digital Library, accessed October 8, 2025, <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/4916/0000/Multiple-diagnosis-based-on-photoplethysmography--hematocrit-SpOsub2-sub-pulse/10.1117/12.482947.pdf>
24. Non-invasive hemoglobin concentration measurements with multi-wavelength reflectance mode PPG sensor and CNN data processing - PubMed, accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/38082910/>
25. Blue as an Underrated Alternative to Green: Photoplethysmographic Heartbeat Intervals Estimation under Two Temperature Conditions, accessed October 8, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC8233784/>
26. Biphasic Effects of Blue Light Irradiation on Human Umbilical Vein Endothelial Cells - MDPI, accessed October 8, 2025, <https://www.mdpi.com/2227-9059/9/7/829>
27. Blue light exposure decreases systolic blood pressure, arterial stiffness, and improves endothelial function in humans - PubMed, accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/30196723/>
28. Measurement of endothelial function using photoplethysmography with continuous correction approach: a pilot study, accessed October 8, 2025, <https://www.ijmedicine.com/index.php/ijam/article/download/2778/1920/0>
29. Heart rate monitoring via remote photoplethysmography with motion artifacts reduction, accessed October 8, 2025, <https://opg.optica.org/oe/fulltext.cfm?uri=oe-18-5-4867>
30. Motion Artifact Reduction in Wearable Photoplethysmography Based on Multi-Channel Sensors with Multiple Wavelengths - PubMed, accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/32182772/>
31. A Non-Invasive Optical Multimodal Photoplethysmography-Near Infrared Spectroscopy Sensor for Measuring Intracranial Pressure and Cerebral Oxygenation in Traumatic Brain Injury - MDPI, accessed October 8, 2025, <https://www.mdpi.com/2076-3417/13/8/5211>
32. Note: Three wavelengths near-infrared spectroscopy system for ..., accessed October 8, 2025, https://www.researchgate.net/publication/260522340_Note_Three_wavelengths_near-infrared_spectroscopy_system_for_compensating_the_light_absorbance_by_water
33. Chapter 17. Cerebral Oximetry | Procedures in Critical Care - AccessAnesthesiology, accessed October 8, 2025, <https://accessanesthesiology.mhmedical.com/content.aspx?bookid=414&ionid=41840242>
34. A multiwavelength frequency-domain near-infrared cerebral oximeter - PubMed, accessed October 8, 2025, <https://pubmed.ncbi.nlm.nih.gov/10211806/>

35. Robust Prediction of Cardiorespiratory Signals from a Multimodal Physiological System on the Upper Arm - PMC, accessed October 8, 2025,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12384275/>
36. A Programmable Gain Calibration Method to Mitigate Skin Tone Bias in PPG Sensors - PMC, accessed October 8, 2025,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12293395/>

B.1.2 Flux AI

connect all the components on the schematic
recommended in the pcb layout for the MSP430FR2475



I'll implement the recommended MSP430FR2475 connections and supporting circuitry in your schematic.

- Steps:

1. Add **MSP430FR2475** 🔍 and define VCC/GND, RST/NMI, TEST/SBW.
2. Add decoupling (e.g., **100nF Capacitor** 🔍 at each VCC within 5 mm; plus rail bulk **1uF Capacitor** 🔍 and **10uF Capacitor** 🔍). Ensure reset pull-up.
3. Add SBW/JTAG programming header and wire VCC, GND, RST/NMI, TEST.
4. Connect all nets and run ERC.

Click Start on the plan bar to proceed. If you prefer an external crystal or a specific programming header, tell me which: 32.768 kHz crystal? SBW 6-pin vs full JTAG?

[Choose SBW header](#)[Select watch crystal](#)[Reset network values](#)

Make sure all packages for capacitors, inductors, and resistors are equal to or bigger than 0805 in size

 [View 1 Knowledge Suggestion](#)

6m ...   



Understood. I'll enforce 0805-or-larger packages for passives and proceed with the MSP430 schematic and wiring.

- We'll document the 0805+ constraint, add **MSP430FR2475** , place only **Resistor**  / **Capacitor**  / **Inductor**  in 0805+, wire power/reset/SBW, and validate via ERC/DRC.

Click Start on the plan bar to begin.

Quick check:

- Is "0805" the minimum (metric 2012) with larger like 1206 allowed?
- Any exceptions (e.g., crystal load caps) or strictly all passives 0805+?

Also, we are using the 48LQFP package for the MSP430FR2475

 View 1 Knowledge Suggestion



1:54 ▼

Got it: implement MSP430FR2475 in 48LQFP, connect recommended nets, and enforce 0805-or-larger passives.

- Add **MSP430FR2475**  (48LQFP), set power/reset/SBW; add reset pull-up **Resistor** .
- Add decoupling: **100nF Capacitor**  per VCC within 5 mm, plus bulk **1uF Capacitor**  and **10uF Capacitor** ; all ≥ 0805 .
- Add SBW **Pin Header 2x3**  and wire VCC, GND, RST/NMI, TEST/SBWTCK.
- Connect nets, set footprints ≥ 0805 , run ERC.

Before I start:

- SBW connector preference: 2x3 0.1 inch or Tag-Connect?
 - Any external crystal required, or use internal clock?
 - Confirm 0805 is the minimum (larger allowed). Click
-
- Any external crystal required, or use internal clock?
 - Confirm 0805 is the minimum (larger allowed). Click Start when ready.

0805 is the minimum (metric included)

 View 1 Knowledge Suggestion

2m ...   

 flux

I will implement MSP430FR2475 48LQFP reference connections with passives ≥ 0805 (metric included).

- Add and wire **MSP430FR2475**  power, reset, and SBW.
- Decouple each VCC with a **100nF Capacitor**  within 5 mm; add bulk **1uF Capacitor**  and **10uF Capacitor**  (all ≥ 0805).
- Add reset pull-up **Resistor**  and SBW **Pin Header 2x3**  ; connect TEST/SBWTCK, RST/NMI/SBWTDIO, VCC, GND.
- Document the 0805-min rule and run ERC.

Click Start on the plan bar to proceed.

Add MCU footprint

Select 0805 capacitors

Add reset pull-up re

► Ready to start.

Clear

Start

Hide Plan ^

#Goal

- Implement MSP430FR2475 (48LQFP) reference connections in the schematic with proper power, reset, and SBW wiring. Use only 0805 (or larger) passive components to meet decoupling and bulk power requirements, and include a 2x3 SBW header for programming/debug access.

#Implementation plan

1. Add the MSP430FR2475 component

1. Select and add the 48LQFP footprint for the MSP430FR2475
2. Ensure all unused pins are terminated per the datasheet recommendations

2. Add power supply decoupling and bulk components

2. Add power supply decoupling and bulk components

1. Place a 100nF decoupling capacitor (0805 or larger) on each VCC pin within 5 mm of the MCU
2. Add additional bulk bypass capacitors of 1uF and 10uF using low-ESR ceramics in footprints of 0805 or larger

3. Configure reset circuitry

1. Add a pull-up resistor (0805 or larger) to the reset line as per the MCU specifications

4. Implement SBW programming access

1. Add a 2x3 SBW programming header to the schematic
2. Connect the header pins to TEST/SBWTCK, RST/NMI/SBWTDIO, VCC, and GND

5. Make necessary net connections

1. Connect VCC and GND between the MSP430FR2475, decoupling/bulk capacitors, and SBW header
2. Wire the reset net from the MCU reset pin to the external pull-up resistor and SBW header

6. Document project properties

1. Add a project property documenting the 0805 minimum footprint requirement (including metric dimensions)
2. Run ERC to verify all schematic rules and connections

#Success criteria

- All VCC pins on the MSP430FR2475 have a nearby 100nF capacitor within 5 mm using an 0805 or larger footprint
- Bulk capacitors (1uF and 10uF) are properly placed and connected with 0805 or larger footprints
- The reset circuit includes the required pull-up resistor

- The reset circuit includes the required pull-up resistor and is correctly connected
- The SBW header (2x3) is fully wired to TEST/SBWTCK, RST/NMI/SBWTDIO, VCC, and GND
- The project property for the 0805 minimum passive footprint rule is documented and ERC passes without errors



Work done

- Updated project description to "MSP430FR2475 48LQFP Reference Board with 0805 Passives, Decoupling, Bulk Caps, Reset Pull-up, and 2x3 SBW Header"
- Added **System Architecture** project property with mermaid diagram of MCU, power subsystem, reset circuit, and SBW header

Remaining tasks

- Add the MSP430FR2475 component (48LQFP) to the schematic
- Terminate unused MCU pins per datasheet
- Place 100 nF decoupling capacitors (0805+) on each VCC pin within 5 mm
- Add 1 μ F and 10 μ F bulk capacitance (0805+)
- Add pull-up resistor on RESET net (0805+)
- Insert 2x3 SBW programming header and wire TEST/SBWTCK, RST/SBWTDIO, VCC, GND
- Connect all VCC and GND nets, plus RESET and SBW nets

- Document minimum 0805 passive footprint rule as a project property
- Run ERC and resolve any errors

Success criteria review

- No capacitors, resistors, or SBW header placed yet, so none of the criteria are met

Next step Let's begin by adding the MSP430FR2475 (48LQFP) symbol to the schematic and assigning its footprint.

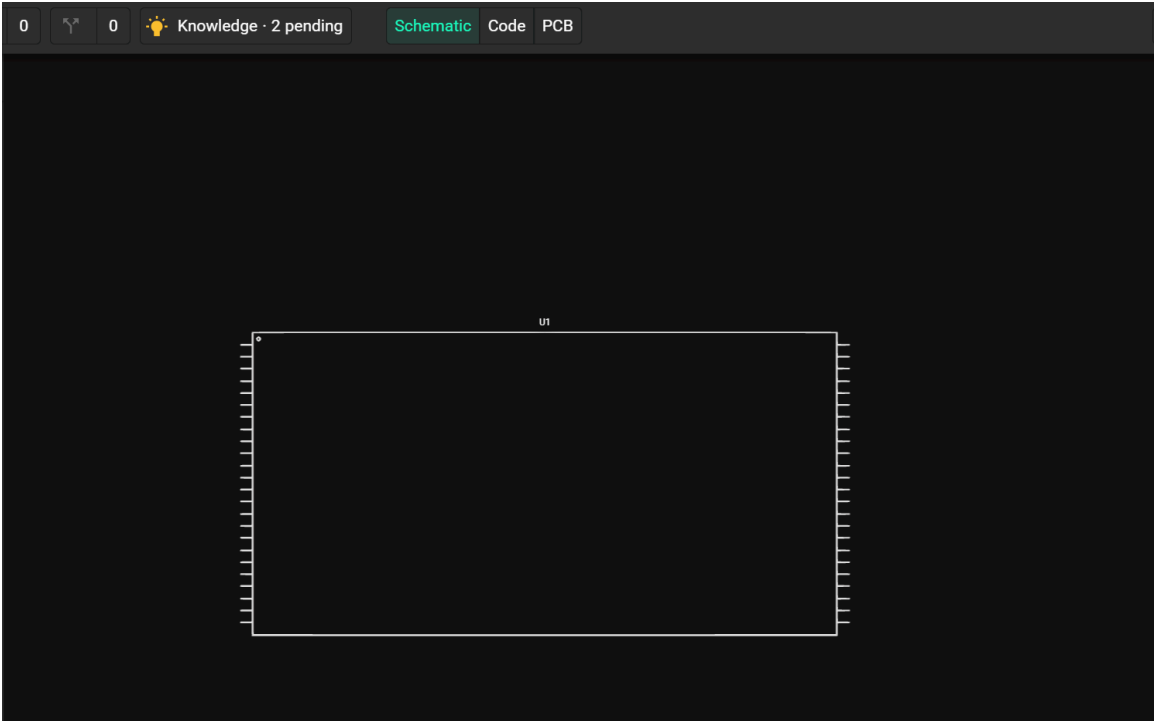
👍 👎 ↻ 📄 ... 2m

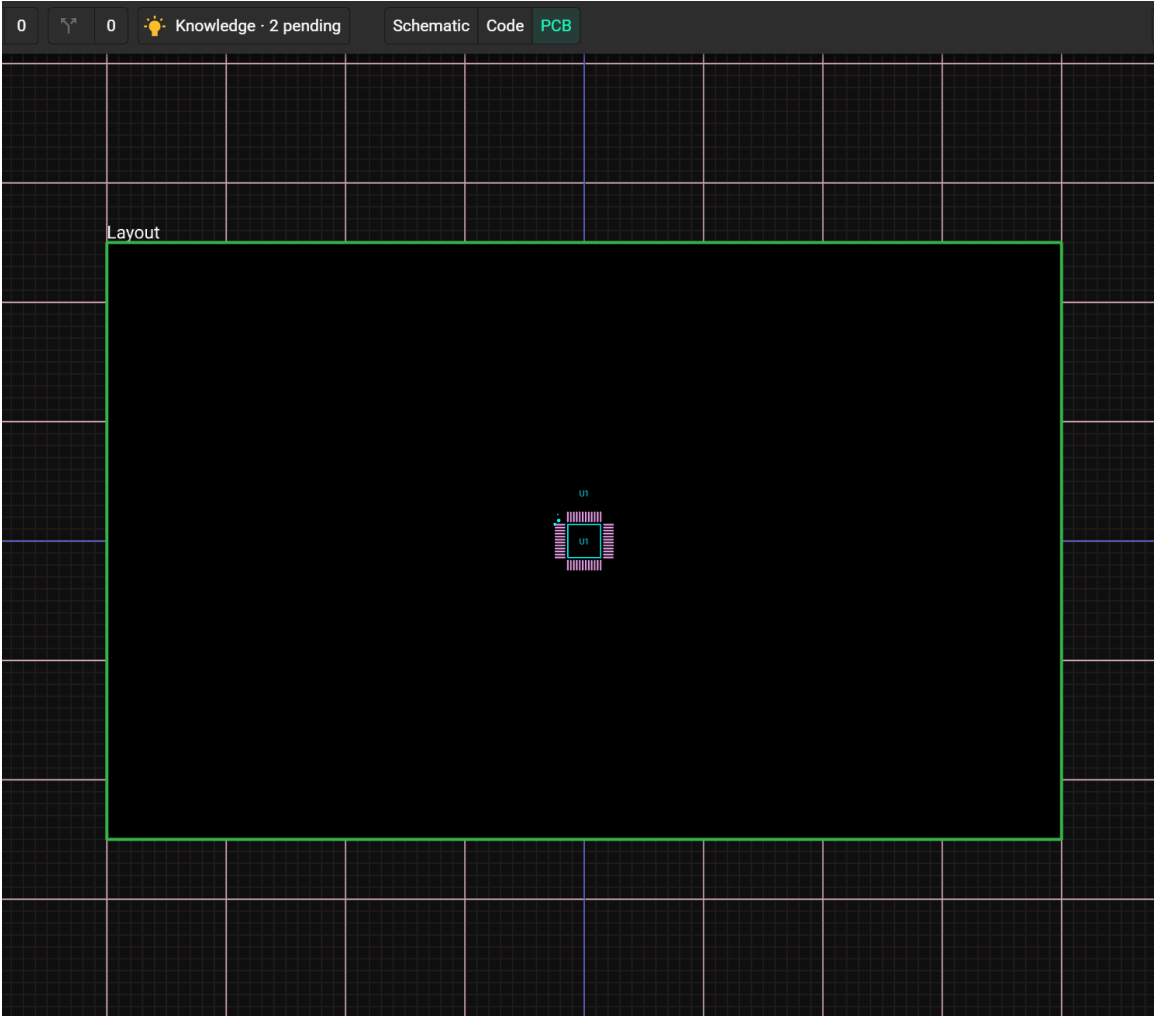


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Project

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Project