

EASE Notifying Feminine Hygiene Pad

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CHAPTER 1 - EXECUTIVE SUMMARY

Some women face challenges when it comes to predicting the flow of their menstrual cycle, which can lead to unexpected leaks while using traditional menstrual pads. These leaks can result in ruined clothing, embarrassment, and stress, affecting comfort and disrupting daily routines. These issues were brought to light by Gabriela Mercado, a student studying finance at the University of Central Florida. After experiencing these problems firsthand, she came up with the idea for a smart feminine hygiene product.

The goal of our project is to address these concerns by developing a smart feminine hygiene product that offers real-time notifications when a pad is nearing its absorption capacity, helping to significantly reduce the risk of leaks.

To achieve this, our project integrates sensors directly into a standard menstrual pad, creating a discreet and effective solution. These sensors continuously monitor fluid levels, detecting saturation in real time. When the pad approaches its capacity, a Bluetooth Low Energy (BLE) module relays this information to a connected smartphone application. The system sends timely notifications to the user, allowing them to change the pad before leaks occur. This proactive approach simplifies menstrual flow management, providing women with a greater sense of security and confidence during their menstrual cycles.

Our ultimate objective is to provide women with greater peace of mind during their menstrual cycles, enhancing convenience and allowing them to go about their daily activities without the constant worry of leaks.

The following document begins by providing an in-depth summary of the project description, including specifying the background, motivation, and inspiration of the project; the expected goals, objectives, and design requirements of which the expected prototype is expected to fulfill and the components required to fulfill these objectives; a description of the primary functions of the project along with a comparison of existing products, highlighting how our project provides a unique solution; the engineering specifications of which our project will focus on to achieve these functionalities along with a brief overview of the hardware and software implementation; and a house of quality to ensure that the engineering specifications meet the expectations and requirements laid forth by the sponsor.

The document then provides an in-depth review of the research and investigation done into currently existing hardware technologies for the MCU, sensor, transmitter / communication module, battery / power supply, PCBs, and voltage regulators, along with existing development environments. Technologies and components were then compared relative to their applicability and usability for our project and carefully selected to fulfill the engineering requirements.

Further research was conducted to determine the industrial standards that heavily dictate the design process for major components, including PCB design, communication protocols, and development environment standards, as these establish the boundaries in which the design must be created. Additionally, real-world constraints were defined to emphasize both the application design restrictions and situational restrictions associated with the project. As part of the research conducted, artificial intelligence platforms were leveraged to aid in maximizing information with efficiency. Usage of such platforms is further provided in Chapter 5.

The document proceeds by providing an in depth review of both hardware and software designs to implement the researched technologies and design considerations previously discussed. Such designs include electrical schematics for the respective components as well as the associated PCB designs for a main PCB and sensor pad PCB implementation. Software diagrams, flowcharts, and logic are presented to showcase the bluetooth connections, implementations, and data transmission for configurations and sensor code.

Implementation of the designed electronic schematics and software if established in system fabrication, depicting PCB layouts and their expected physical integration with a feminine hygiene pad. SOLIDWORKS CAD models are presented to provide a visual representation of such implementation to present the ideal implementation of a future design. The prototyped version developed in Senior Design 2 is also presented.

Testing methods of both the hardware and software design are established to ensure that the electronic system is capable of meeting the functions and performance requirements presented at the beginning of the document. Additionally, testing methods for the essential performance metrics of which the device will be assessed is described, along with methods testing the device's capability to meet the environmental and physical constraints determined in real-life application. These methods and designs reflect the plan implemented for integration, prototyping, and testing performed in Senior Design 2.

Administrative content in regards to the budget, financing, and responsibilities associated with the project design process is presented at the end of the document. A project milestone for both the research and development performed in Senior Design 1 along with designs is presented, as well as the project milestones for Senior Design 2. Appendices referring references, copyright permission, data sheets of components, and AI prompts and outcomes are also provided.

CHAPTER 2 - PROJECT DESCRIPTION

This project aims to design and develop a robust embedded system solution tailored to a specific application, integrating both hardware and software components to achieve a seamless user experience. The motivation behind this project stems from the growing need for efficient, compact, and user-friendly electronic systems in modern applications such as automation, communication, and smart devices. The project's primary goal is to

deliver a functional prototype that meets defined performance, usability, and reliability standards. To achieve this, clear objectives have been established, including implementing core functionalities, ensuring low power consumption, and maintaining cost-effectiveness. The design requirements focus on key performance indicators such as response time, interface compatibility, and system scalability. The system will feature multiple user-focused functionalities, with a detailed description of each component's role, backed by precise engineering specifications. Supporting this design are a comprehensive hardware block diagram, a software architecture breakdown, and an initial prototype illustration. To ensure alignment with user needs and engineering trade-offs, a House of Quality analysis has also been developed, guiding the design process toward optimal outcomes.

2.1 Project Background and Motivation

As part of the reproductive process, females regularly experience a multitude of physiological side effects associated with the female menstrual cycle, the most notable being physical bleeding. With significant variation in flow, duration, and consistency between individuals, females can have drastically different experiences. Some develop a seemingly regulated cycle length or consistent flow amount, making the use and timing of feminine hygiene products easily predictable while others experience inconsistent cycle lengths from abnormally short, to abnormally long with flow amounts varying from extremely heavy to extremely light. With the latter being highly unpredictable, a female with this type of menstrual cycle may find it difficult to determine when to replace a fully used hygiene product or how often to replace such products which can lead to issues impacting daily life such as embarrassment, inconvenience, or messiness from excess menstruation leakage.

Our Senior Design project aims to resolve this issue by developing a product targeted to the female population that allows users to know exactly when a feminine hygiene product currently being used has reached its maximum capacity and must be replaced. This would provide users with real-time data on blood volume, instantaneously sending alerts to prevent unwanted leaks or discomfort, greatly enhancing user confidence and peace of mind. A project like this would require our group to work cohesively in every step of the engineering design process to ensure a working and effective product is produced. Significant researching, brainstorming, planning, and innovation will be required to design an integrative product, combining software and hardware to effectively meet the desired goal, allowing our team to work together and overcome challenges.

This project was presented to us by Gabriela Mercado, a finance student at the University of Central Florida, an entrepreneur, and the sponsor of this project. She developed the concept of this project after having multiple menstruation leakage experiences at 16 which resulted in embarrassment and stained clothing. These experiences inspired her to develop a product that would notify her of fluid volume within a feminine hygiene product. Developing such a product would positively impact a significant portion of the

female population who experience the menstrual cycle for a large portion of their lifetime. Completion of this project could benefit females who experience irregular blood flows and schedules, young females experiencing periods for the first time and navigating how to manage them, or other females who prefer to manage their menstrual cycles stress-free. Thus, our team is motivated to positively impact and directly improve the daily lives of everyday people through the development of this product over other militarized or corporate projects.

Completion of this project can also provide other significant benefits beyond regular maintenance of menstruation leakage. With a system that can detect and notify users of leakage volume, this product has the potential to act as a health monitoring device. By providing precise insights on menstrual flow, the system possesses the capability of tracking and maintaining data that can identify and indicate if an individual is experiencing abnormal menstrual flows or periods relative to their previous cycles that can be indicative of developing health concerns. Additionally, tracking and identifying these abnormal patterns can proactively aid in the identification of hormonal imbalances or gynecological conditions. Early detection of these health issues would provide users with the opportunity to obtain timely medical consultation and intervention, greatly improving overall health and minimizing any risks and health complications associated with the menstrual cycle.

2.2 Goals, Objectives, and Design Requirements

The EASE project centers around a system that alerts its user when their menstrual product is used or at capacity. There are many implementations that can accomplish this goal. With this in mind it doesn't matter whether or not the device is disposable, reusable or embedded in the menstrual product. The main goals of the EASE project stay the same. That is to create a device which can accurately detect when a menstrual product is at capacity or nearing capacity and successfully notify its user. This splits the project into a few pieces of tech which our group is aiming to create, the sensor, the transmitter, the pcb/integration and the alert system.

The Sensor

Overall goals

- Accurately detect when the user's menstrual product is at or nearing capacity.
- Perform the aforementioned detection with an accuracy of 75% or higher.
- Collect sensor data both at the users request as well as passively.
- Comfortable form factor

Advanced goals

- Fully reusable sensor.

Stretch goals

- Additional health sensors such as pH level, blood iron levels, or any other useful data that can be effectively measured through the blood.

The Transmitter

Overall goals

- Reliably sends data between the sensor and alert system.
- Sends data both at the user request as well as passively.

Advanced goals

- Can communicate between both Android and IOS devices.

Stretch goals

- Communicated with our own wearable implementation of the alert system.

The PCB/Integration

Overall goals

- Comfortable and discrete form factor.
- Waterproof and reusable
- Integrates the sensor and transmitter.

Advanced goals

- Flexible PCB design
- Washable “sleeve” to house the PCB

Stretch goals

- Replaceable adhesive patch design for more comfort or discrete form.

The Alert System/App

Overall goals

- Alerts the user when the menstrual product is at capacity or near capacity.
- Can be easily paired with the PCB/Transmitter.

Advanced goals

- Provides current sensor readouts and updates at the users request.
- Available on both Android and IOS.

Stretch goals

- Ability to select the brand/type of menstrual product being used for more accurate data.
- Wearable implementation

Goal Summary

In summary the goals we are hoping for are broken down into basic, advanced and stretch goals. The basic goals our project is hoping to achieve are comfortable design, reliable capacity sensing, and a reliable notification/alert system. The user should be able to use and rely on our device to provide them with an accurate notification and prevent leakage without sacrificing comfortability. The advanced goals are ones that further improve the quality of the basic goals, here we are looking to improve battery life, app compatibility,

and a reusable design. These advanced goals build upon the basic goals and are designed to improve the quality of the product.

The third category of stretch goals are ones that go one more step further but either pose a bigger challenge or greatly alter the design in such a way that would change some previous goals in terms of objectives to reach them. These stretch goals include a wearable alert system option, more advanced tracking/data tracking like blood oxygen levels, and a large range of compatibility with existing menstrual products. While these stretch goals do not conflict with the basic goals they do conflict with the traditional objectives used to accomplish some of these basic goals. These are summarized below.

- **Basic Goals**
 - Accurately detect when the user's menstrual product is at or nearing capacity with an accuracy of 75% or higher.
 - Reliably sends data between the sensor and alert system.
 - Comfortable and discrete form factor.
- **Advanced Goals**
 - Fully reusable sensor.
 - Can communicate between both Android and IOS devices.
 - Provides current sensor readouts and updates at the users request.
- **Stretch Goals**
 - Additional health sensors such as pH level, blood iron levels, or any other useful data that can be effectively measured through the blood.
 - Communicated with our own wearable implementation of the alert system

In the next sections of chapter 2, the objectives needed to accomplish the basic, advanced, and stretch goals, how they conflict, and what the thought process is in regards to how we will approach which objective is more suitable for our project is described.

2.2.1 The Sensor

The EASE project is very dependent on the sensor. A sensor able to accurately and precisely determine the fluid level absorbed by a menstrual product that also does not come with a loss of comfort or reusability is difficult and poses the most challenges. But because of this the objectives are clearly laid out for us. The biggest objectives we are looking for are relating to the comfortability, reusability, and data reliability.

To achieve comfortability a great objective is a small or soft form factor. For reusability we need a sensing solution that is cohesive, most likely not embedded in the product, and easily cleanable or sanitizable. And for data reliability we need a sensor that can recognize the volume, weight, or surface coverage of the product. Other important objectives are to find a sensing solution that is low powered or passive, this can further improve comfort and size but may come at the cost of price, precision, or accuracy.

Multiple solutions immediately come to mind such as a fluid pressure sensor, a weight sensor, or something similar to an array of contacts that are set to short when in contact

with fluids like a level sensor. Each of these options have their drawbacks: the fluid pressure and weight sensors are difficult to ensure comfortability and the weights and pressures can differ depending on the capacity of the menstrual product, blood density, and multiple other factors.

The “level sensor” built from contacts sounds novel and can be distributed across the entire surface of the menstrual product giving good volumetric data without needing to worry about the factors that plague the previous sensor options but it too struggles with checking all the boxes. Imagine we embed the contacts in the second layer of the menstrual pad; this option gives good coverage and with small enough contacts could be completely comfortable but the reusability factor goes away almost completely.

If instead we decide to create a level sensor band that can be placed around the border of the menstrual pad to detect when it is reaching capacity, this may be a more reusable option but lacks comfort and extra information that we were hoping to gather such as percentage full. In addition to the conflicts listed previously the sensor we eventually land on must be able to remain functional in its environment for a week on average. This means the sensor needs to be relatively robust, it will be in a high moisture, warm, and sometimes high pH environment. To achieve the accuracy goal we are looking for the sensor must be able to operate the entire duration without wear being an issue. The objectives and goals of the sensor collide with each other and make it the most difficult part to satisfy in the EASE project.

2.2.2 The Transmitter

The transmitter has goals which are more direct and clear cut. Reliable data transmission, compatibility with common devices, and both passive and active data transmission. For reliable data transmission and compatibility their objectives align, the most used methods of data transmission follow the trend of the most reliable. The most obvious option is Bluetooth. With that in mind implementing Bluetooth is a large objective, with that we add size and power consumption. It will be important to find and use a Bluetooth implementation that is as small as possible, low power data transmission devices are not unheard of, but may cost more than the average user is willing to pay for consistently in the case that the product may become disposable.

For both passive and active data transmission, the transmitter will need to have a processing unit that can interpret signals sent from the user, this again adds size and power consumption. All of the goals we want to achieve come at the cost of an increase in size and power. This means that another big objective will be to find a solution that either reduces the size and power to a manageable extent or passes some of the objectives along to the PCB / integration method.

At the integration level, issues like form factor and size are large concerns due to the comfortability decreasing as the size increases. If comfort can be found another way on the PCB side, the transmitter can afford to use more power or have a larger footprint. A stretch objective that could solve multiple problems here is to incorporate the wearable

alert system, then we could use our own simplified communication protocol and forgo the need for a larger bluetooth IC. An antennae can be etched into the pcb and NFC can be used to communicate with the wearable element. This reduces size and power but skips the goal that centers around common device compatibility.

2.2.3 The PCB

The PCB/Integration is another contentious part in the EASE project. Just like the sensor there are many ways to accomplish the goals we outlined like comfortability, and reusability but some of the objectives to accomplish these goals can conflict. One goal that may be the most difficult to accomplish will be integrating the sensor and the transmitter/receiver. Collecting data from the sensor in most applications is fairly straightforward and the sensor is either directly mounted to the pcb or the sensor has its own housing and wire/cable is run to the necessary places.

To create a pcb that is comfortable to wear the objectives are split, mounting the sensor to the pcb and placing that inside or on the menstrual product will most likely be uncomfortable while running a ribbon cable or other wires from the menstrual pad also is uncomfortable and may take away from the discrete form factor goal. This creates two goals, create a pcb that is either flexible, soft, or small enough to attach to the sensor directly, or create a comfortable ribbon/wire harness option that connects to a PCB that is then later attached somewhere more comfortable such as a waistband or garment.

If the first of these objectives is chosen then additional goals spawn such as a waterproof PCB design, an effective cleaning and sanitation method, and a method for easy attachment/detachment. If the second objective is chosen it will create objectives such as external garment mounting design and an effective way to use the extra pcb room we acquire. As stated in the last section if the PCB can achieve comfortability without sacrificing size the transmitter can afford to change or flex its goals/objectives.

Another objective that must be adhered to is the safety of the PCB/integration. Both methods still require a pcb to be kept close to a person's skin, things such as heat, abrasion, and chemical irritants will need to be eliminated not just for comfort but for safety. Common solder contains lead which should not be kept on the skin for long periods of time, common solder joints are also typically very abrasive and can scratch or break skin very easily. If a low power solution is found then heat may not be an issue. Body heat from the user must also be considered in design for electronic safety.

2.2.4 The Alert System / App

The alert system's goals and objectives follow that of the transmitter's. We want something that is compatible with common devices, gives the user up to date data, the ability to request or monitor the data, and fast response times. In order to achieve these goals just like the transmitter we need a common transmission method like bluetooth, we need a way to integrate and process the data received from the sensor or transmitter. For

this, it's most likely an application will be needed, the user could easily from there view the data as well.

Fast response times are congruent with the aforementioned communication methods and should not be the most difficult objective to fulfill. When we take into account the stretch goals such as the wearable implementation and selection of menstrual products some of the other objectives change. The wearable implementation removes the necessity of a communication protocol IC and gives the transmitter and PCB more freedom in their options. The option to choose the menstrual product used can potentially improve the accuracy and precision of some of the sensing applications like the weight or fluid pressure sensors.

An additional objective arises from the ability to select the menstrual product and that is cataloging popular products. We would need a relatively large database of products, their capacities, and other information. Then we would need a method of storing and integrating this data. We could store all the data on the app but if we choose a wearable design it may mean we cannot pursue this objective. The alert system does not struggle with any of its objectives.

There are some trade offs but those are due to conflicts that arose from the other parts. The alert system needs to be built to cater to the rest of the system, a place the user can interact with or receive the data the system collects. It is not limited much by cost, size or power constraints and is most likely something that will need to be developed either last or only when key design concepts are decided upon.

2.3 Description of Features / Functionalities

The following sections outline the expected features and functionalities the ideal product should be capable of achieving, primarily in terms of physical capabilities rather than electronic capabilities. The prototyped version of this project will prioritize the electrical capabilities to ensure proof of concept which can later be taken and innovated to meet the physical capabilities. These engineering specifications and their corresponding functionalities will be provided in later sections.

2.3.1 Main Features

The main feature of the EASE PAD is notifying the user of the fluid volume in the feminine hygiene product, through technological means. According to a survey done by Gabriela, 88.6% of the 210 responses replied that they would consider using a pad or tampon that would notify the user when it is full or close to full. In that same survey, 77.6% of participants have had anxiety of leaking while in public.

By knowing the amount of fluid in the hygiene product, the user will know when to change said product to prevent leakage onto their clothing, as leakage can ruin clothes,

cause embarrassment, and just in general be messy. This feature provides convenience to the user as they will not have to waste time going to the bathroom to check if their pad is about to leak. It would also reduce their anxieties about leaking in public. The product should remain external (pads or underwear) rather than internal (tampons, disks, menstrual cups), as this adds to the ease of use and peace of mind to the user. As the device is external, it will also be reusable as to reduce the costs for users and to prevent additional waste.

As pads come in different sizes and brands, another feature of the project would be to be able to input the brand and size of the pad into the app so that the product is compatible with different sizes of pads. Since we are adding external hardware, we would like our product to be as comfortable as possible, which means the sensors will be separate from the PCB and additional housings. According to the Mayo Clinic [1], periods typically last 2 to 7 days, which means the battery life of our product should last long enough to accommodate a typical cycle. The information we are collecting is low frequency data, meaning we should be able to make this device low powered to make the battery last this long.

2.3.2 Extra Features

Some extra features that we would like to implement, should time allow it, are sending the information about the capacity of the pad to a custom made wearable, and additional health sensors in the pad. Through the custom wearable, users would not have to worry about bringing their phone everywhere they go and would still be able to get valuable information. This wearable could resemble something like a fitness tracker that has a screen and can buzz the user when the pad is at or near capacity.

A lot of health information can be extracted from just blood alone, and if we can add more sensors to the product we can provide users with additional information about their health, rather than just the amount of blood in their pad. To make the product as reusable and user friendly as possible, an adhesive patch, like the ones used on diabetes patches would be used to stick the device on the thigh of the user.

2.4 Existing Products

Currently, the market offers various menstrual hygiene products, each designed to address different needs related to comfort, flow management, and environmental sustainability. While these products serve their intended purposes effectively, they don't fully address the unpredictability of menstrual flow or offer features that could provide real-time alerts to users about threshold capacity levels. Below, we discuss existing products and their capabilities, along with their limitations in terms of addressing the issue of menstrual leakage and predictability. These limitations should clearly indicate the problem at hand and how the designed product should differ from these products.

2.4.1 Menstrual Discs and Cups

Menstrual cups and disks are reusable products inserted into the vaginal canal to collect menstrual blood. Menstrual disks, such as those made by companies like *Flex* or *Softdisc*, sit below the cervix, while menstrual cups, like those from *DivaCup* or *Lunette*, use suction to stay in place and prevent leakage. These products have gained popularity due to their environmental benefits and cost-effectiveness, as they can last several years with proper care. However, users often struggle to determine when the cup or disk is nearing its capacity, as these products typically do not include any sensor or alert mechanisms. This results in a risk of overflow and leakage, particularly for those with irregular flow patterns.

2.4.2 Reusable Pads and Leak-Proof Underwear

Leak-proof underwear, such as *Thinx* or *Modibodi*, and reusable pads offer an environmentally friendly alternative to disposable pads and tampons. These products rely on fabric layers that absorb menstrual flow, and they can be washed and reused. While they do reduce the amount of waste produced during menstruation, they do not provide any feedback to the user about their saturation level, often leaving users unsure of when leakage may occur. This can lead to similar concerns about overflowing and staining as with other products. These limitations highlight the need for a more advanced system, like the EASE Notifying Feminine Hygiene Pad, that monitors and alerts users before leaks happen.

2.4.3 Smart Hygiene Products

Some recent advancements in the menstrual product space include the development of "smart" tampons and pads. These products, still largely in the prototype phase, are designed to detect moisture and send signals to a connected device, notifying users when a product is full. One example is *LOONCUP*, a smart menstrual cup with built-in sensors to monitor fluid levels and detect health indicators [2]. However, most of these products face significant challenges in terms of reliability, comfort, and battery life. Many smart tampons and pads are not yet widely available, and their real-world usability is limited due to high costs, concerns about device durability, comfort, and issues with integration between hardware and software.

2.4.4 Traditional Tampons and Pads

Traditional tampons and pads, such as those offered by brands like *Always* and *Tampax*, have long been the standard solution for managing menstrual flow. While they are widely accessible and available in various absorbency levels, they come with inherent limitations. Once their capacity is reached, they can no longer prevent leakage. Without any mechanism to notify users when the product is full, it is easy for leaks to occur unexpectedly, especially for individuals with heavy or irregular flows. This underscores the need for a product like the EASE Notifying Feminine Hygiene Pad, which aims to fill this gap by providing users with timely notifications before they reach leakage risk.



Figure 2.4.3.1 LOONCUP Device (from LOONCUP)

2.5 Engineering Specifications

The preceding sections depict the objectives, goals, and vision of what the final project should achieve. In order to convert this idea to a demonstrable product that successfully fulfills the project goal, a set of engineering requirement specifications must be clearly defined. These specifications serve as both a contract between our team and our sponsor, Gabriela Mercado, and a grading metric between our team and the committee that clearly states what the project will be capable of upon completion.

Such engineering specifications are defined below in Table 1 which identifies both the quantitative and qualitative metrics of what the completed prototype should meet. The highlighted specifications are ones that we find to be demonstrable to our review committee. We really wanted to prioritize size and weight while also balancing reliability and accuracy. The battery life metric is one that we believe may be over our necessary battery life value but would work well with the reusable aspects we hope to achieve with this device. In the physical specifications we wanted to include safety as this project is going to be a wearable device.

EASE Notifying Feminine Hygiene Pad	
Quantitative Metrics	
Max. Surface Area	125 cm ³
Max. Weight	10 g
Temperature Limitations	Up to 46°C [3]
Environmental Rating	IP 35 [4]
Volume Accuracy	±1 mL
Response Time	Transmits within ~1 s of product reaching ~75% and 95% capacity
Battery Life	7 Days
Performance Reliability	Provides an accurate notification 90% of the time
Qualitative Metrics	
User Interface	Data should be displayable via an app on a mobile device
Communication	Transmitter should be capable of communicating real-time data to the user's mobile device, including current blood volume within the hygiene pad when prompted.
App Specifications	Sends a notification when pad is nearing maximum capacity
Physical Specifications	Compatible with the most common types of external feminine hygiene products
	Product is reusable
	Comfortable and lightweight such that it is virtually unnoticeable when in use
	Pliable and able to conform to reasonable shapes as necessary for the user
	Able to withstand contact from bodily fluids including but not limited to blood, water, sweat, and discharge
	Device is safe for its expected application

Table 2.5.1 EASE Engineering Specifications and Requirements

2.6 Hardware Block Diagram

The figure below corresponds to the hardware block diagram for our project. This diagram presents a high-level visual of the major components of our electronic device and how they are expected to integrate and interact with each other, providing a system overview. Additionally, the figure represents a simplified version to clearly indicate the relationships and flow of how the system will operate to generate the desired outcome. Aspects of the diagram are color coded to reflect work distributions and responsibilities as indicated in the corresponding legend.

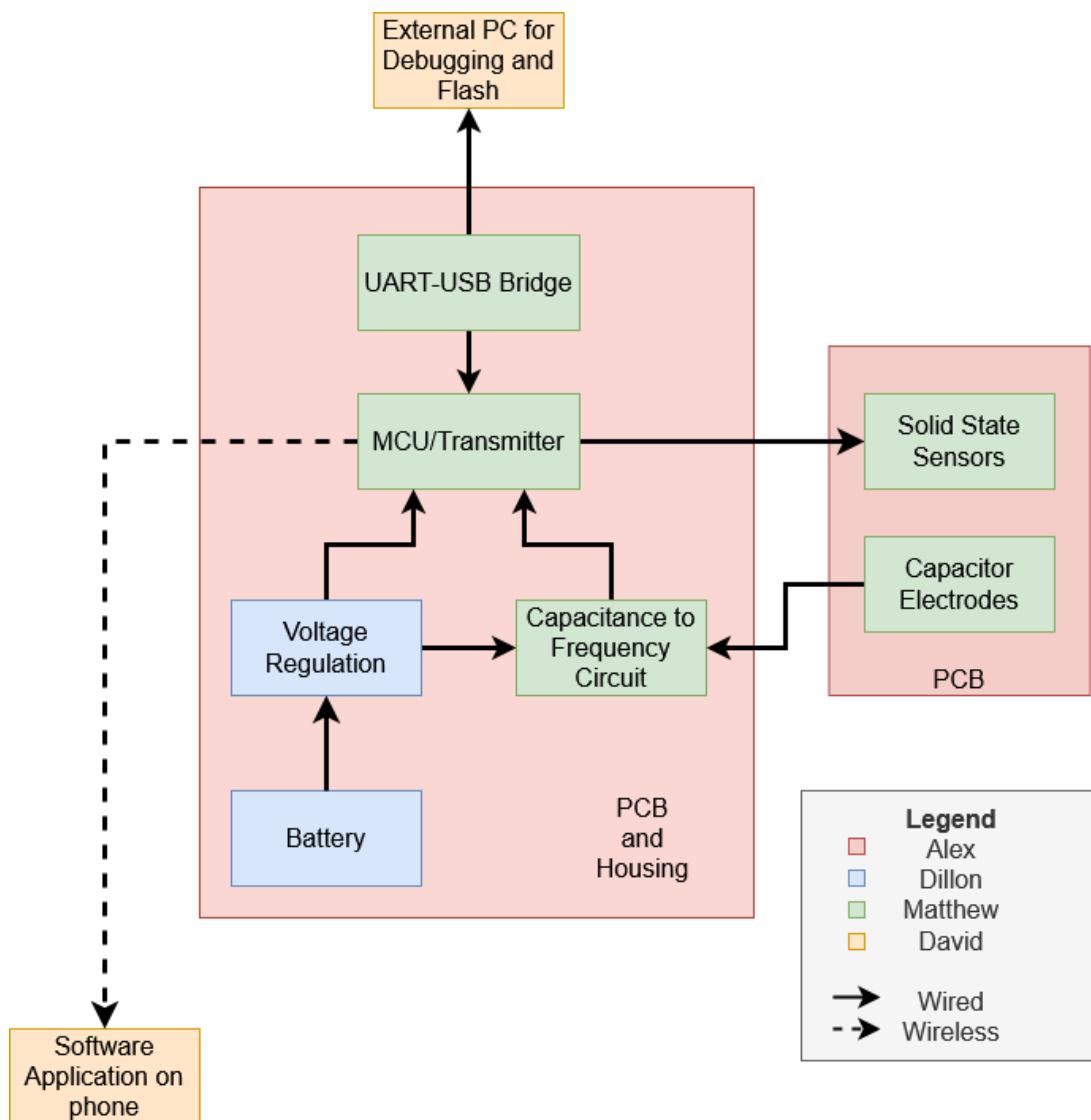


Figure 2.6.1 Hardware Block Diagram (created by Authors)

2.7 Software

The following sections outline the performance goals and expectations that the device should be capable of adhering to in regard to software.

2.7.1 Basic Goals

The primary software goal of the EASE Notifying Feminine Hygiene Pad project was to deliver a reliable and timely notification to the user's mobile device, informing them when their hygiene product has reached a critical threshold and needs a replacement. This core functionality required continuous interaction between hardware and software components, where the sensor detects the fluid levels, and the transmitter sends this data to the mobile device via Bluetooth.

The system's basic software goals include:

1. *Seamless communication*: The mobile app must be able to receive data from the transmitter reliably and without a delay lasting more than a few seconds. This ensures the user receives a notification when their pad is at or near capacity.
2. *Accurate monitoring*: The software should process sensor data and evaluate it to assess if the feminine hygiene product has reached the predefined capacity limit. This evaluation must be performed continuously or at set intervals.
3. *User-friendly notification system*: The mobile app must notify the user when the hygiene pad is near full capacity or when it has reached the capacity threshold. The notification should be clear, easy to understand, and actionable.
4. *Compatibility*: The software must be capable of functioning across both Android and iOS devices to ensure accessibility for a wide range of users.
5. *Low power consumption*: Both the transmitter and the mobile app should be optimized for low power consumption to prolong battery life, particularly during the passive monitoring.

These basic goals lay the foundation for a reliable, functional product. We wanted to ensure users are notified in a timely and accurate way to avoid leakage and improve overall convenience.

2.7.2 Software Diagram / Flowchart

The following sections outline software flowcharts, simplifying the expected software performance.

2.7.2.1 Overview Flowchart (Includes Hardware Scope)

Figure 2.7.2.1.1 shows our ideal software flowchart, its interactions with our hardware, and how we hoped the system would interact with the user. The sensor subsystem in the

chart is an aggregate of the two sensing applications we used and the threshold is a predetermined mix of sensor values provided from both sensors. The user was ideally able modify this threshold value but for our initial design we wanted to keep things simple in order to establish proof of concept which is why there is no option for communication back to the user. The associated legend also provides a visual representation of the breakdown of responsibilities for each respective component and / or subsystem.

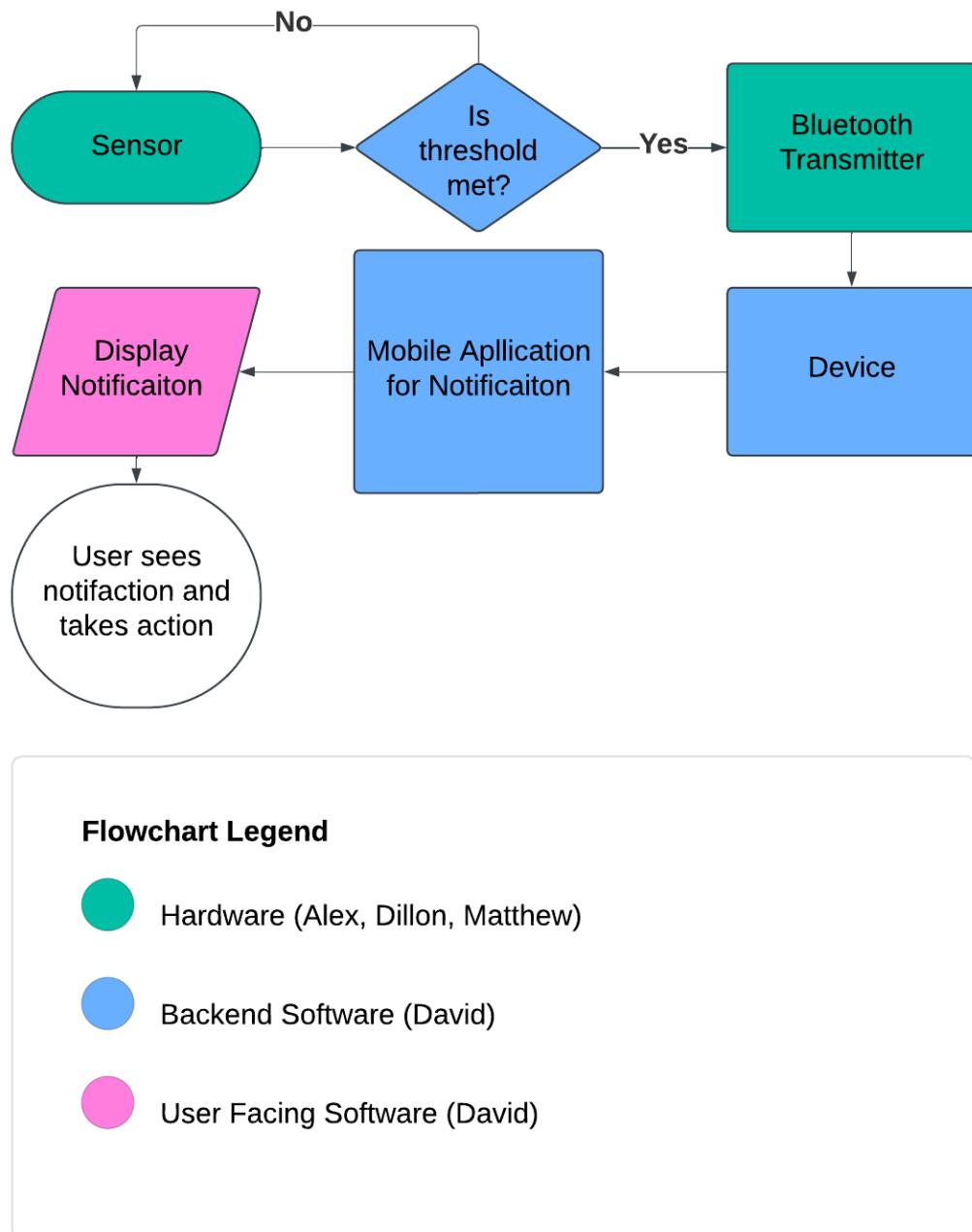


Figure 2.7.2.1.1 Project System Flowchart (created by Authors)

2.7.2.2 Software Flowchart

The chart below is an overview of how the software will specifically interact once the bluetooth detects the sensor has reached its threshold capacity:

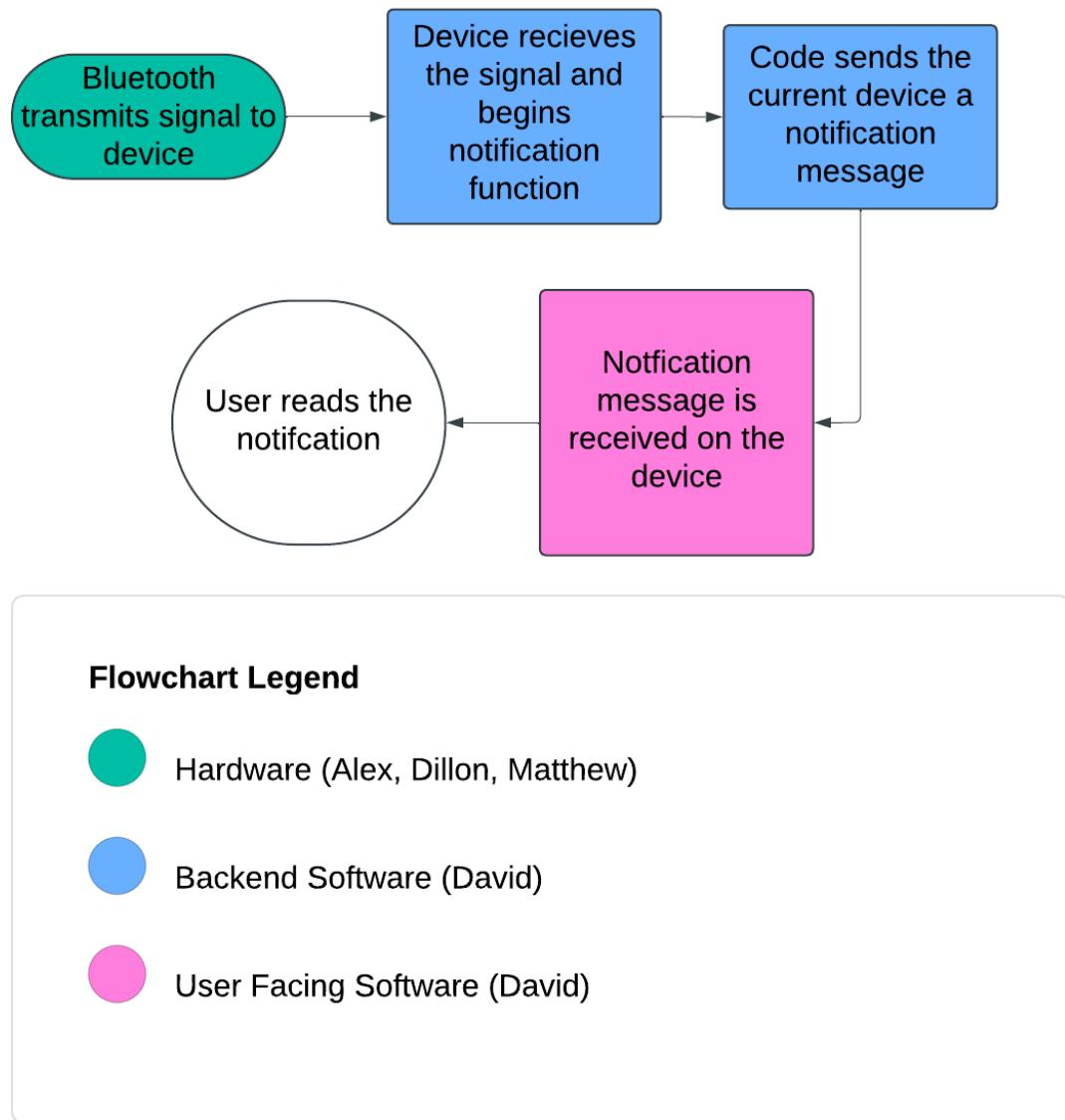


Figure 2.7.2.2.1 Software Flowchart (created by Authors)

2.8 Prototype Illustration

The figure below shows a prototype illustration of how we would initially design the project. The method of sensing is subject to change as more research and testing progresses but the overall concept still stands. The left represents a pad as a feminine hygiene product while the right represents our electronic device. Our device will involve sensors that will integrate with the menstrual products perimeter in such a way to

optimally measure fluid volume and moisture. The device will then send a signal to the user's phone (represented at the bottom) that will alert the user via a notification. It would be ideal if the user could also interact with the device via their phone and request current volume data or possibly lower the alert threshold as well.

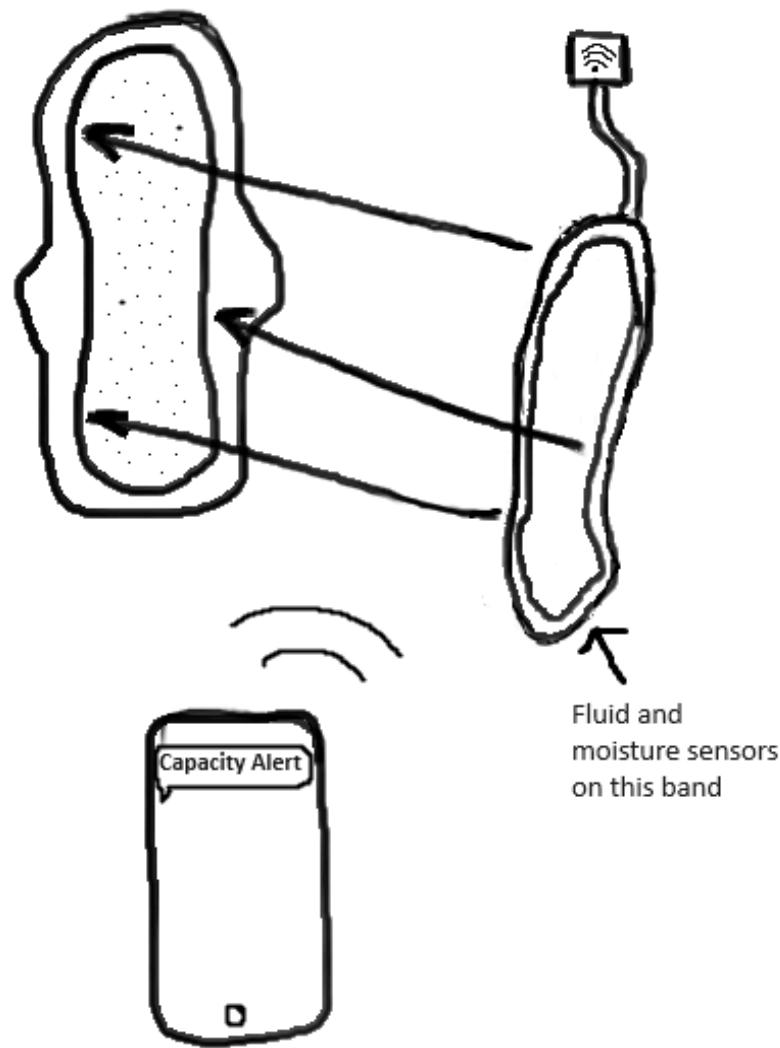


Figure 2.8.1 Prototype Illustration (created by Authors)

2.9 House of Quality

The figure 2.9.1 below is the corresponding House of Quality for our project, translating customer requirements into the technical features of the product. This tool allows us to connect the customer needs with engineering characteristics and specifications to ensure that those needs are prioritized in the design process to meet customer satisfaction. This figure will allow us to use these priorities to make better engineering and technical decisions as this device is developed to meet customer expectations. What is not reflected

in the house of quality is the weight each category carries in respect to the project. We very much value comfortability which means product weight and length are weighted more than the other categories but only slightly. We believe that this figure does well at balancing qualities we value and does not include any characteristics that we don't believe carry as much weight in the design process.

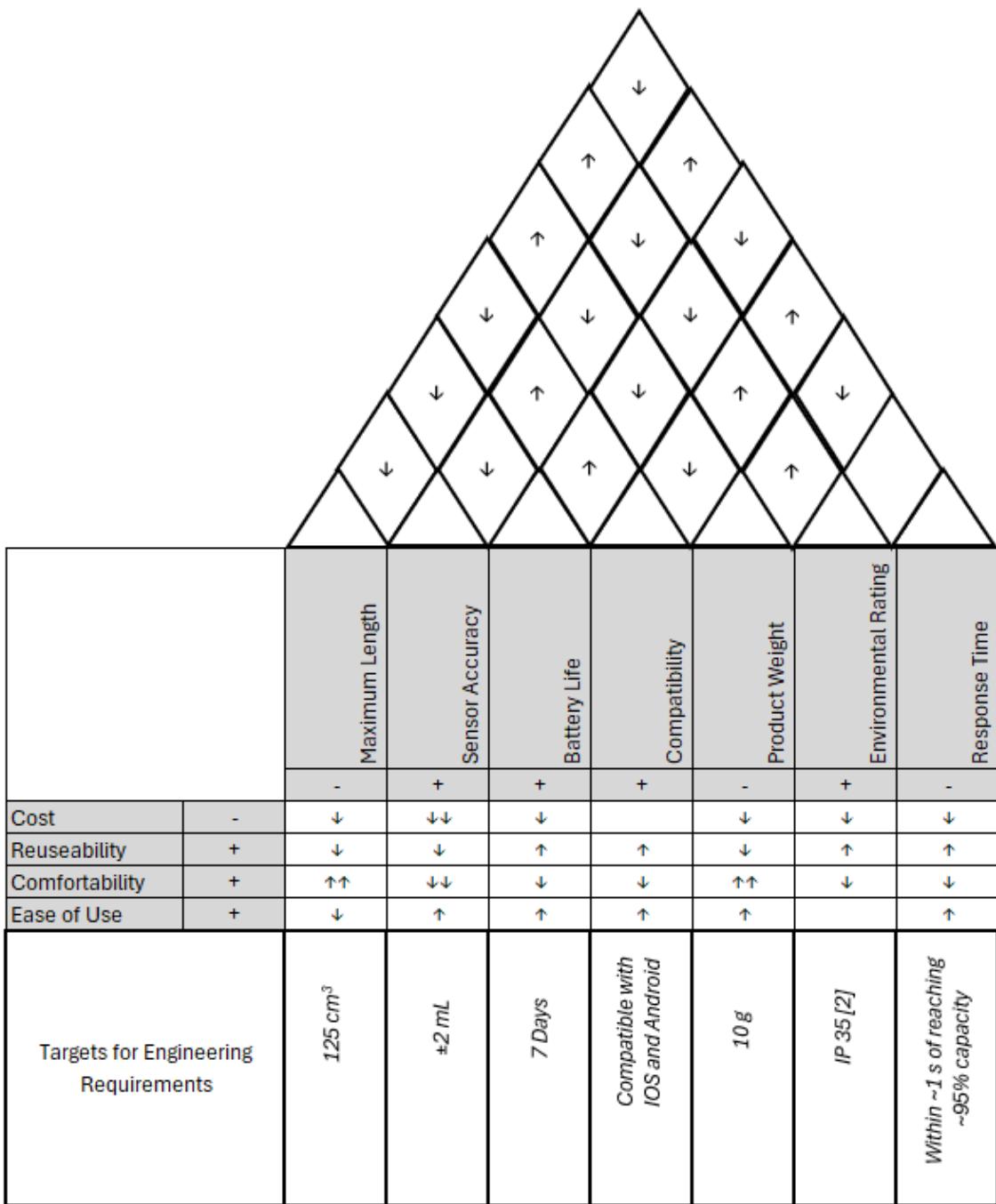


Figure 2.9.1 House of Quality Chart (created by Authors)

CHAPTER 3 - RESEARCH & INVESTIGATION

Researching and investigating are crucial steps when designing an electronic prototype, as they lay the foundation for a successful and functional final product. Thorough research helps designers understand user needs, technical requirements, available components, and potential challenges, ensuring that the prototype is both practical and innovative. By investigating existing solutions, industry standards, and emerging technologies, developers can make informed decisions, avoid common pitfalls, and identify opportunities for improvement. This careful planning not only saves time and resources but also increases the chances of creating a reliable and effective electronic device.

3.1 Technologies

Researching the various technologies that exist in regard to electronics is vital for designing effective and up-to-date electronic systems. From microcontrollers and sensors to communication protocols and power management solutions, the field of electronics offers a wide range of tools and components that serve different functions and purposes. Understanding these technologies allows designers and engineers to make informed choices that enhance performance, efficiency, and reliability. Staying current with technological advancements also opens the door to innovation, helping to create smarter, more compact, and more energy-efficient electronic devices. The following sections summarize the research performed in understanding the various technologies that exist that will be crucial in achieving the engineering specifications and functionalities expected from this project.

3.1.1 MCU

The MCU is a relatively important piece of the project because it dictates multiple design parameters and variables related to our goals and objectives. In order to create a small and discrete product the MCU size needs to match. In order to integrate a high accuracy sensor the MCU needs to be compatible. The MCU needs to be able to facilitate communications between the sensor, transmitter, and even alert system. The MCU largely determines the operating voltage and power draw of our design.

Researching MCUs came down to isolating variables that correlate to our objectives and goals and finding possible options. From our objectives we know we want a small package size, relatively large amount of GPIO pins (around 15 pins minimum), low power capabilities, and communication capabilities. From our engineering specs we can gather a few more variables such as an operating temp less than 46 C, weight less than 5 g and IP35 environment rating.

3.1.1.1 Integrated Communication / RF MCUs

One of the first variables to research is the communication capabilities our possible MCU could offer. The most common type of RF communication implemented in MCUs and the type we are most interested in is Bluetooth. Multiple types of Bluetooth protocols and versions are available in multiple MCUs but what we are most interested in is power draw and range. For our project we want to look for the lowest power draw that meets our range of around 1 meter maximum. Using an RF MCU we can eliminate the need for an external transmitter and receiver and reduce both the cost and space constraints of the project.

With this there are assumed to be drawbacks such as increased price, MCU size, potential MCU operating temperatures, and additional needs for the PCB such as a transmission circuit and antenna. While prices will vary based on packages, additional features, and order quantity, we can take a look at a specific package size such as QFN 32 (Quad Flat Package 32 Pin) for both RF and traditional MCUs and compare the prices.

Using data from Mouser.com [5], [6] we can see that the price difference is negligible. MCU size is another one that is expected to be a problem but when looking at our engineering specifications we can see our desired size is less than 125 cm cubed. Package sizes offered for these RF transmitters are as small as 2.5mm x 2.6mm with larger sizes being around 5mm x 5mm. The expected larger MCU size is still within our range and does not affect the design in a large manner.

Operating temperatures are the unknown variable to keep track of here. The temperature would be a factor of multiple things such as MCU uptime, tx and rx frequency, and ambient temperature. The addition of a transmission circuit and antenna do add size to the project's footprint but we thought it is still very possible to save space this way. There were not many bluetooth modules with internal antennas which would mean the bluetooth modules are purely extra space. These factors were the same in other MCUs therefore we believed that the benefits outweigh the drawbacks when choosing RF MCUs.

3.1.1.2 MCU Packages

MCU/Integrated Circuit packages were initially important for this project because a large portion of our project involves size constraints. Because of this it was important to research the possible package types and determine which ones are more desirable for our project. Packages can be categorized into groups based on how they mount, their shape, and pin layout [7]. Through-hole packages and surface mount are the two main methods of mounting. For through-hole packages it is common to only see three sub categories based on pin layout, 1 directional inline, bi-directional inline, and matrix packages. One and two way directional through hole packages are named as such due to how their pins are aligned on the package. 1 way directional refers to a single row of pins numbered in order, 2 way directional or bi-directional refers to 2 rows of pins on opposing sides of the IC.

The typical sizes of these directional inline packages (DIP) range from (6x4)mm to (64x14)mm. Matrix packages are ones in which the pins are arranged into an array or matrix on the bottom side of the IC, these packages are more versatile and their sizes have a large range similar to the DIP packages. For our project it's important to note that through-hole packages were not initially preferable due to their size and discomfort. As discussed further in the PCB section of chapter 3, we wanted to use a design that favors comfort which leads us in the direction of flex PCBs and through-hole packages both didn't work very easily with flex PCBs and would add to discomfort due to exposed pins.

For surface mount packages the previous three sub-categories still exist but differ slightly. The directional package types are no longer inline due to them no longer being through-hole but instead the pins are now arranged as an outline. The pins now are bent into an L shape to rest against the PCB and are more commonly in a quad directional format, surrounding all sides of the IC. The matrix arrays also change due to them no longer using through-hole pins and instead either use a ball grid array or electrode buds, sometimes referred to as lead-less or non-leaded packages.

The surface mount packages are the ones we wanted to look further into because they suited our initial design more in terms of size and comfort. The surface mount variants of the directional package are the Small Outline Package (SOP) and Quad Flat Package (QFP) [8]. The SOP package is very similar to the through-hole bi-directional inline package, also known as the Dual Inline Package or DIP. The SOP has either L or J shaped leads on either side of the IC and is a very common package due to its easy mounting style and relatively strong structural integrity. The QFP is almost the same as the SOP but instead has leads on all four sides of the IC. The QFP and SOP sizes range from (4x4)mm to (40x40)mm, comparable to the matrix through-hole packages such as the Pin Grid Array (PGA). The QFP is even more popular than the SOP due to its higher pin count, small footprint capability, mounting style, and thermal performance. The higher cost and more difficult assembly process were notable drawbacks but had far outweighed its strengths when we made the comparison for deciding our MCU originally.

Both the SOP and QFP have non-leaded counterparts where electrode buds are used instead of pins. Some notable packages that use this configuration are the Quad Flat Non-Leaded package (QFN), Very-thin Quad Flat Non-Leaded package (VQFN), and Thin-Quad Flat Non-Leaded package (TQFN). The non-leaded counterparts are very similar in size range to their QFP counterparts but offer a smaller mounting area which is different from the package size. The surface mount variants of the matrix style pinout, the Ball Grid Array packages (BGA) were another great option and can usually support much more advanced applications while keeping a small area.

The BGA packages can support high pin counts, are more efficient than QFPs and QFNs, have better thermal performance than QFPs and QFNs, and don't need to sacrifice size to achieve these benefits. It's also important to note that for RF MCUs we want a package that favors signal integrity and "cleaner" electrical characteristics. The BGAs pin layout favors better electrical characteristics and therefore becomes much more suitable for RF

transmissions than other packages. The BGAs while being better in almost every category do suffer because they are more complex than the other package designs.

Testing, maintaining, and replacing these packages is often not worth the investment which makes them risky for a prototype design. Another package type to keep in mind is the Chip Scale package (CSP) package. These packages are ones that are created from individual dies and are processed at the wafer level [9]. This produces an even smaller and complex package with the advantage of direct contacts to the wafer from the solder ball contacts which improves thermal dissipation, electrical characteristics such as resistance and efficiency, and IC speed. These package sizes range from (2x2)mm to (10x10) mm. The downside of these types of packages are that they are wafer level packages. The integrity and protection these packages have to offer are much lower than other package types and can prove difficult to use in humid environments.

Our objectives, goals, and requirements give us things to note in order of importance. We want a small footprint or size to be discrete and comfortable, a low power option due to the battery operated nature of the design, good RF communication, reliability, and a GPIO pin count that can facilitate any sensor option(s) we choose during the design.

Looking into size on Table 3.1.1.2.1 we can see that CSP and BGA are very good options, they are the smallest options and coincidentally the largest GPIO in counts but are susceptible to their environments which makes them unreliable. Good power and RF characteristics come from the designs with best lead contacts and interconnects, the shorter the contact the better and the smaller the size the better. BGA and CSP are also very good for power and RF but again suffer from unreliability. QFNs and QFPs on the other hand are slightly worse than BGAs at all of these characteristics except reliability where they are much more comfortable and structurally sound.

The through-hole packages are large, uncomfortable, and do not mesh well with flex PCBs making them the worst option. They do have the advantage of high GPIO pins but we only need a max of around 20 GPIO pins to accommodate any sensor option which the other packages can achieve. The QFN and VQFN are the options that fit this criteria the best. These packages normally range from 32-48 pins, sizes from (3.5x4.8)mm to (5x5)mm as shown in Table 3.1.1.2.1 which is perfect, offer good electrical characteristics for power consumption and RF communication and are reliable. Because of this QFNs and VQFNs were our first choice when looking for packages with BGAs second.

3.1.1.3 MCU Manufacturers

MCU manufacturers are very similar in most regards. Most manufacturers produce many different MCUs with multiple different available packages and specs. Because of this we instead need to look for the differences that do matter in terms of our project. The key things we can look for when determining a manufacturer is sourcing, environmental information and rating, developer options and support, and familiarity.

Package (Mounting Type, Pin Layout Type: Package Name)	Cost	Size	Power and Performance Qualities (Divided into groups by Pin Type)
Through Hole, Directional Inline: SIP (Single Inline Package)	Lowest cost to produce.	Large, (6x4)mm	Lowest Power Efficiency and Performance. Higher lead inductance and capacitance.
Through Hole, Directional Inline: DIP (Dual Inline Package)	Lowest cost to produce.	Large, (6x4)mm	
Through Hole, Matrix: PGA (Pin Grid Array)	Low but variable cost.	Variable Size.	
Surface Mount, Outline: SOP (Small Outline Package)	Low Cost. very popular.	Small. (4x4)mm to (40x40)mm	Poor Power Efficiency and Performance.
Surface Mount, Outline: QFP (Quad Flat Package)	Low Cost. similar to the inline packages and very popular.	Small. (4x4)mm to (40x40)mm.	
Surface Mount, Non-Leaded: QFN (Quad Flat Non-Leaded Package)	Low Cost. Comparable to the Leaded counterparts.	Small. (4x4)mm to (40x40)mm	Good Power Efficiency and Performance. Lower inductance and capacitance.
Surface Mount, Non-Leaded: VQFN (Very-Thin Quad Flat Non-Leaded Package)	Higher Cost. Mostly due to the small package size.	Very Small. (3.5x4.8)mm.	
Surface Mount, Ball Grid: BGA (Ball Grid Array)	Higher Cost. due to complexity and size.	Smallest. as low as (2.7x2.7)mm.	Best Power Efficiency and Performance.
Surface Mount, Ball Grid: CSP (Chip Scale Package)	Highest Cost. due to the wafer level package processing	Smallest. (2.5x2.6)mm	Increased speed and reduced inductance and capacitance.

Table 3.1.1.2.1 Package Comparison

Sourcing is a very important and sometimes overlooked aspect of design. It fits cohesively with budgeting and time management making it important for projects with strict deadlines and small overheads. Common part retailers such as Digikey and Mouser will traditionally list information about parts and manufacturers such as minimum order quantity (MOQ), lead time, and price per quantity which makes sourcing fairly straightforward. We want to look for a MOQ that fits our design scope and budget so less than around 20 parts per order at our budgets max of \$10 for the MCU. Our project's scope only requires one working prototype currently so this \$10 budget should suffice.

The second piece of important information is lead time. As discussed earlier we are looking for an RF MCU in a VQFN or QFN package with a size range of less than or equal to (6x6)mm. Taking a look at mouser we can sort by these characteristics and determine what lead times work for us regarding when prototyping needs to be completed. When looking into lead times the data provided from Digikey and Mouser is useful but does not give the full picture, instead we can take a closer look into the individual manufacturers and figure out more about their general lead times, production volume, and expected prices. Price per quantity is information that we can get directly from our chosen supplier such as Digikey and Mouser. Because our project is small it's much harder to purchase directly from a manufacturer and instead we must rely on third party retailers which restricts a lot of control we want. Sourcing issues can be the death of any project which is why it's important to check stocks, lead time, product lifespan, and current prices. It may become apparent that our MCU of choice is not possible to source and changing our design to account for that is important.

Environmental rating is another important factor when researching manufacturers. Manufacturers will not always give every product of theirs the same environmental rating but most will adhere to standards set in place by governing bodies or associations such as the RoHS regulations or the IEEE standards. It's important for us to check which standards and regulations our manufacturer adheres to colloquially and what environmental rating is given individually to the product we want to use. There is also the Ingress Protection or IP ratings given to specific products which is not to be confused with the environmental information. The IP rating of our product is very important in choosing a specific MCU and can lead us to a decision but generally differs greatly based on the application the product or MCU was designed for.

Developer options and support is one of the biggest factors we will base our decision on. Many MCU manufacturers will use their own proprietary libraries, developer boards, and development environments. We want to look for an MCU manufacturer that provides the easiest path to design with their product without sacrificing the capabilities of our project. This concept ties in directly with familiarity. Many of us have used Arduino MCUs during our time at UCF and are familiar and comfortable with its IDE called Arduino IDE. Familiarity matters because every project is constrained by time. Learning a new manufacturer's process and nuances is time that could be better spent developing with a manufacturer that is more familiar. Looking into possible manufacturers we first narrow down the group by looking exclusively into RF MCU manufacturers, a search on Mouser shows three big manufacturers that we should research.

3.1.1.4 Texas Instruments RF MCUs

Texas Instruments is a staple in the semiconductor market especially in the United States. Most engineers in the US will have experience with their products and development environment. Their CCxxxx RF MCUs are a great option, they are offered in QFN and VQFN packages that provide more than enough data pins to support any sensor type we choose to use, have much more processing power than necessary, offer high pin counts, and use a development environment that is familiar with the team. The CC2640R2L in particular offers a low power standby current of $1.5\mu\text{A}$ with full RAM retention [\[Data-1\]](#).

Sourcing is good with these MCUs, they are currently in stock and are purchasable in low quantities. The CC2640R2L is RoHS compliant [\[10\]](#) for the (5x5)mm VQFN package. TI also lists it as a wearable fitness monitor and smart tracker for possible applications. While the prices for these MCUs is slightly higher than other MCUs at around \$4.17 [\[11\]](#) at the time of writing this, that is a manageable price. Issues I have with this MCU stem from its development support. To program this MCU a development board is needed which is currently in low stock with a long expected lead time of 12 weeks. This may be okay to proceed with but other options provide more reassurance in terms of sourcing.

3.1.1.5 STMicroelectronics RF MCUs

STMicroelectronics produces multiple RF MCUs that fit our design criteria. Their STM32 RF MCU meets the criteria needed for our design and is both offered in favorable package sizes. The BLUENRG MCU is another RF MCU offered by STM but with the sole function of a low energy network processor. The STM32 MCUs have readily available development boards at a much cheaper price of \$44 [\[12\]](#). The STM32 MCUs vary and have multiple different models and packages which is great for sourcing concerns. The software STM uses for these MCUs is the STM32 Cube and its expansion package the X-CUBE-BLE1 [\[13\]](#). Both are unfamiliar to the team which makes these even more unfavorable but not completely out of the picture. Neither MCU mentioned whether or not they were RoHS compliant but does state that their products follow the IPC-1752 standard and are RoHS compliant on their website meaning they do have more compliant MCUs than TI which only offered it for a few packages.

3.1.1.6 Infineon Technologies RF MCUs

Infineon produces only one line of RF MCUs that meet our package and size requirements, the CYW207xxx. These MCUs are offered in a (5x5)mm QFN32 and do have the networking and performance capabilities needed for the project and at a reasonable price [\[14\]](#). They are RoHS compliant, provide enough GPIO pins to facilitate any sensor option we choose, and are compliant with Bluetooth 3.0. These chips were originally designed and manufactured by Cypress which was acquired by Infineon in 2019 [\[15\]](#) and due to that finding developer support and additional documentation is very difficult. Due to this I cannot find a developer board option which almost instantly eliminates any of these MCUs as an option. Due to the QFN32 design we would need to design and build our own development board and learn the JTAG flash process needed to

program the MCU which is valuable time and effort. These MCUs were an interesting option considering they were cheap and small. They have a programmable keyscan matrix interface which I thought could end up being very useful for the matrix sensor option discussed later on.

3.1.1.7 MCU Summary

Below in Table 3.1.1.7 we can see the comparison between the three manufacturers RF MCU's. Highlighted in green is the MCU that is most favored initially for this project. The criteria we used for this comparison is mostly found on the MCU's respective data sheet. It is important to note that for this comparison the development environment was one factor that had significantly more weight than other categories. We believed that working in a familiar and comfortable development environment would make our project massively easier.

3.1.2 Sensor

The sensor is the hardest and most important part of this project to get right. Our sensor needed to accurately and reliably detect volume to a degree that provides benefit to the user. This means that detection needed to occur at all stages of volume percentage and with consistent accuracy. Detecting volume accurately for only the first 20%-30% does not help the user, but detecting volume accurately during the last 20%-30% does help the user. This means our strategy for sensor implementation prioritized continuous accuracy above all other sensor benefits.

The other big priority initially when designing or choosing a sensor application is size and comfort. If the product is 100% accurate for 100% of the uptime with perfect results but completely unwearable it's useless. This is the balance we needed to get right for our project to work. When detecting or sensing the volume of any liquid electronically there are multiple different conventional methods such as time of flight sensors, capacitance sensors, pressure differential sensors, float level sensors, and solid state short sensors.

3.1.2.1 Time of Flight Sensors

Time of flight sensors send a propagating wave pulse towards the liquid volume and measure the time before a return pulse is measured to determine the current volume of a fluid inside a container with known dimensions. This can be done with an RF wave, lidar or ultrasonic waves [16].

These sensors are great because they are reliable and accurate when used in a controlled environment. The downside to these sensors is that they need a controlled environment, a rigid fluid container is needed, they are a large option, and they are not the best suited for small applications.

	TI CC2640R2L	STM STM32WBA54KGU 6	Infineon CYW207
Cost	\$4.17	\$7.39	\$6.56
Packages	VQFN, QFN	UFQFPN	QFN
Size	5.1x5.1 mm	5x5 mm	5x5 mm
Total Pin and GPIO Count	32, 15	32, 18	40, 16
Standby Current Draw	1.5 μ A	0.9 μ A	1.6 μ A
Operating Voltage	1.8 to 3.8V	1.71 to 3.6V	1.90 to 3.63V
Development Environment	Code Composer Studio IDE	STM32CubeIDE 3rd Party IDEs	Support Discontinued
Sourcing	MCU and Dev board in stock	MCU and Dev board in stock	MCU in stock. Dev board EOL
Bonus Peripherals	12 bit ADC UART, I2C, I2S Integrated Temp Sensor	12 bit ADC UART, I2C, SPI Touch Sensing Controller 2 low power 16 bit timers	Serial wire debug I2S, PCM, PDM2 I2C, UART ADC, Keystream Matrix interface 6x 16-bit PWMs

Table 3.1.1.7 MCU Comparison

3.1.2.2 Capacitance Sensors

Capacitance sensors can be used by insulating two terminals of a capacitor and placing them in the fluid's container, as the fluid passes through the gap between the capacitor plates the dielectric constant changes and the capacitance changes [17], as the fluid level decreases or increases the amount of fluid in between the two capacitor plates changes which can be seen in the changing capacitance of the circuit element. These sensors are less accurate than other options and need to be calibrated based on the fluid being measured and the size of the fluid container but do work well in small environments and can be implemented in a small space. They also have the benefit of simplicity which

makes them capable of being used more unconventionally or even for discrete measurements.

3.1.2.3 Pressure Sensors

Pressure sensors work in many different ways, one common way to measure the volume of a fluid with a pressure sensor is to use the fact that liquids are non compressible, an air tube is fitted to the airtight tank in which the liquid is kept and as the liquid level rises the air is compressed and measured by the sensor. Another way a pressure sensor could be used is through typical hydrostatic pressure, if the pressure sensor is placed at the bottom of the fluid's container it can measure the change in pressure as the water level increases and an airtight tank is not needed.

This pressure calculation can be achieved in multiple different ways, a typical piston and potentiometric setup is a cheap and relatively robust method, a capacitor can also be used similar to the last sensor mentioned but instead of the dielectric change being the driving variable it is instead the difference in distance between the capacitive plates, piezoelectrics generate electric charge when compressed and that changes depending on the amount of compression, and thin film can be used by measuring the films electrical properties as it deforms due to pressure [18]. These sensors are versatile, simple, and relatively reliable making them a good option, some applications of these sensors don't need extra information such as fluid container dimensions and ambient pressure to give valuable data which is very useful. The downsides of these sensors is that they can be large and implementing them in a small space or on a small scale can be very difficult.

3.1.2.4 Float Level Sensors

Float level sensors are another group of sensors that work in many different ways similar to pressure sensors. The general concept is to have a buoyant part that moves with the fluid level be detected by another auxiliary sensor, this can be done with a floating magnet and hall effect sensors, or dipstick style rods that use potentiometer to measure the length the floating rod is held at [19]. Generally this sensor needs a defined and static fluid container to perform well, using this sensor at a small scale in a small space is not very intuitive and most likely is the wrong choice for our project. The use of a sensor like this would also require the complete redesign of the menstrual product we intend to use with it. I could imagine that a float level sensor could potentially be used in a menstrual cup but a pad is much harder to justify.

3.1.2.5 Solid State Sensors

The solid state short sensors are different from the others because they are not continuous, these sensors use exposed contacts usually arranged in an interlocking comb pattern to detect where the liquid level is based on shorted data pins. Assuming the liquid you are measuring is conductive the short sensor simply detects when two contacts are shorted and the data pin registers a high signal. It's similar to the capacitive sensor in how it is installed but does not measure any continuous data and just extrapolates based on

which contacts are shorted. It's a very simple method but has some unique advantages due to its simplicity. This sensor's benefits are the simplicity of its sensing method and the simplicity of its implementation, both of those characteristics make its applications more malleable than the other sensor options. Its drawbacks are its simplicity, its data can only be discrete, it relies on exposed metallic contacts which can wear over time in the fluid, and it's susceptible to inaccurate readings because of those reasons.

3.1.2.6 Sensor Summary

The problem with almost all the sensor options listed here is that they interpret their data based on a static known fluid container and its dimensions. All of these sensors except some applications of the pressure sensor need to know the volume of the tank, their relative position to the bottom of the tank and the dimensions of the tank to determine the fluid volume accurately. For our project we are trying to determine the current liquid volume inside a menstrual pad.

Menstrual pads deform and absorb, they are worn by people who are constantly moving around, they fill with multiple different liquids with different weights and densities, and are placed in areas where comfort is wanted the most. This means that our sensor solution will need to measure the volume of the liquid in a less conventional way. This is where I think the solid state sensor is the most interesting, this sensor option allows for a more discrete approach to measuring the liquid level of the pad which is more flexible in implementation. Instead of measuring to a precise fluid volume at all times we can instead just rely on when the fluid level is nearing its peak or at discrete intervals and this would still provide valuable data to the user.

Continuous methods ended up still working for this project, the pressure sensor could have been used with multiple uncertain variables while still producing a valid result but it may have proved difficult to handle the variance in data results due to the uncontrollable and varied environment it was used in. Capacitive sensing became our main source of detection as we further developed the project. We appreciated the continuous sensing method it offered us while still retaining relatively precise and accurate data points. Table 3.1.2.8 highlights the sensor types most fitted to work with our project. It also displays the characteristics by which the sensor types are judged.

3.1.3 Transmitter / Communication Module

The goal of this project is to notify the user when their pad is about to leak, and to accomplish this goal, we need a way to send information to the user's phone. To do this, we need some sort of wireless transmitter/communication module that is able to communicate with a smartphone. The most common communication protocol used by smartphones is Bluetooth or WiFi. We will be using Bluetooth to communicate because it requires less power and it is a lot simpler than WiFi. More specifically, we should use Bluetooth Low Energy as it reduces the power consumption, and the device is limited on power due to running off small batteries.

Feature	Time of Flight Sensors	Capacitance Sensors	Pressure Sensors	Float Level Sensors	Solid State Sensors
Accuracy	High in controlled environments	Less accurate, needs calibration	Versatile and reliable	Needs defined, static fluid container	Discrete data, less continuous accuracy
Simplicity	Complex setup required	Simple, easy to use unconventionally	Varies by type (e.g., piston, capacitive, piezoelectric)	Simple but needs auxiliary sensor	Very simple implementation
Environ. Dependency	Sensitive to environment	Needs dielectric constant of liquid	Can work with varied environments	Limited to specific container setups	Requires conductive liquid
Best Use Case	Controlled environments	Small, defined environments	Versatile applications	Large, defined fluid containers	Flexible applications
Drawbacks	Needs controlled environment, large	Less accurate, needs calibration	Can be large, difficult in small spaces	Not intuitive for small scale	Discrete data, susceptible to wear

Table 3.1.2.8 Sensor Comparison

3.1.3.1 Integrated in the MCU

The simplest way to add Bluetooth capabilities to our device is to use a microcontroller that has Bluetooth built into it. This would eliminate the need for a separate module for Bluetooth, which in turn, would reduce the size of the device, which we are trying to minimize. While it does free space on the PCB it's important to remember the MCU does not contain an integrated antenna or transmission circuit. This will still need to be added to the PCB and not only that, transmission circuits and PCB antennas are very difficult things to design and tweak, each new design will require waiting on a new PCB to test.

Other preemptive testing can be done via simulation beforehand which will become increasingly important if we choose an RF MCU.

3.1.3.2 Certified Bluetooth Modules

Another option is to integrate a certified Bluetooth module into our PCB. These modules contain all the necessary hardware to add Bluetooth to a project, like antennae and processors. They typically interface with the MCU through a standard serial communication protocol like UART or I2C.

3.1.3.3 Transmission Module Summary

While using a dedicated bluetooth module is a great idea because of the simplicity and ease of implementation we agree that using an integrated RF MCU with our own PCB antenna and transmission designs is the better option. Figure 3.1.3.3.1 explains our general thought process behind this decision. While we will have more of a struggle implementing the transmission using an RF MCU we can reduce space which is very very important to us in this project. It also has the added benefit of slightly reducing the price and freeing up a few gpio pins. The decrease in price could end up being important if we decide the device can only work as a non-reusable disposable electronic device.

	Size	Ease of implementation
Certified Bluetooth Module	Adds to the size of the PCB	Easy
Integrated into MCU	Reduces Size	Hard

Table 3.1.3.3.1 Bluetooth Module Size Comparison

3.1.4 Development Environment

Choosing the right development environment is a critical decision that can significantly impact the efficiency, quality, and success of a software project. Different development environments offer varying features, tools, and levels of compatibility that cater to specific programming languages, project requirements, and team workflows. By comparing available options, developers can identify the environment that best supports their goals, enhances productivity, and minimizes potential issues during development. Making an informed choice not only streamlines the coding process but also contributes to smoother collaboration and more reliable deployment.

3.1.4.1 Integrated Development Environments (IDE)

Integrated Development Environments (IDEs) are powerful software applications that provide comprehensive tools for programmers to write, test, and debug code efficiently. They typically combine a source code editor, compiler or interpreter, debugger, and other

features such as version control and intelligent code completion into a single interface. IDEs are designed to streamline the development process, reduce errors, and boost productivity by offering an all-in-one solution tailored to the needs of developers. As the complexity of software projects grows, IDEs have become essential tools for both beginners and experienced programmers alike.

3.1.4.1.1 Arduino

Arduino's IDE is a simple, open-source development environment primarily used for programming Arduino microcontrollers. It's favored for rapid prototyping due to its ease of use and availability of various libraries. Arduino IDE offers features such as autocompletion, code navigation, and a live debugger. Arduino IDE uses a variant of the C++ programming language known as Arduino Sketch. The Arduino platform supports an extensive collection of libraries to simplify interaction with hardware peripherals. The IDE includes built-in functions to handle input/output operations, making it easier to develop hardware-software interfaces for sensors and actuators.

3.1.4.1.2 STM32Cube

The STM32Cube ecosystem is a complete software solution for STM32 microcontrollers and microprocessors. It is a combination of software tools and embedded software libraries, providing a full development environment. The IDE includes STM32CubeMX, which is a graphical tool that helps generate and configure initialization code for peripherals.

STM32Cube also supports C and C++ development and has built-in debugging and real-time analysis features. This IDE simplifies working with the STM32 microcontrollers by providing ready-to-use middleware, firmware libraries, and examples, which can speed up the development process in embedded systems when using the STM32 microcontroller series.

3.1.4.1.3 Code Composer Studio

Code Composer Studio (CCS) is an integrated development environment (IDE) developed by Texas Instruments (TI) specifically for their microcontrollers and processors, such as the MSP430 and Tiva series. It provides a powerful suite of tools, such as an editor, project build environment, and debugger to assist in embedded development. CCS also integrates TI-RTOS, which allows for real-time scheduling and resource management, which is something crucial for embedded applications.

Code Composer Studio supports C and C++ development, making it the ideal option for low-level embedded programming, where direct access to hardware is essential. CCS also offers energy trace technology meaning that it can help optimize power consumption in embedded devices, such as a battery operated system like the ease project. CCS is available for download in Windows, Linux, and macOS devices, or used via cloud by visiting the TI Development Zone.

3.1.4.1.4 WICED

Infineon acquired Cypress Semiconductor, however the recommendations still remain. For the CYW207, the recommended development environment is to use WICED Studio, the native IDE tailored for Wi-Fi and Bluetooth development. WICED stands for Wireless Internet Connectivity for Embedded Devices. WICED Studio comes with a Software Development Kit (SDK) that supports Bluetooth and Wi-Fi protocols. The WICED Studio SDK also includes profiles, stacks, and a variety of example applications for BLE, Bluetooth Classic, and Wi-Fi integration. Though the CYW207 MCU is not the best option, it is a great course of action to research and understand the native development environment for it and compare it to other options. WICED Studio is available for Windows, macOS, and Linux, making it an extremely accessible IDE across different operating systems. Like other IDEs, WICED Studio supports C and C++ programming languages as these two are the most standard programming languages for embedded systems development.

3.1.4.2 Programming Languages

Programming languages are the foundational tools that developers use to communicate with computers and create software applications. Each programming language has its own syntax, rules, and strengths, making it suitable for specific types of tasks, whether it's web development, data analysis, system programming, or mobile app creation. Understanding the differences between languages and choosing the right one is essential for building efficient, effective solutions. As technology evolves, so do programming languages, continually adapting to meet the changing needs of the software development world.

3.1.4.2.1 C++

C++ is an extension of the C language, incorporating object-oriented programming features. C++ is frequently used in embedded systems that require more complex architecture, such as those involving sensor networks or real-time data processing. Both Arduino IDE and Code Composer Studio support C++ for embedded development. C++ allows for modular code design with classes and objects, improving code readability, reusability, scalability, and organization, making it quite useful when multiple components, such as sensors and transmitters, need to be managed efficiently. It is also known for its performance, efficiency, and control over system resources and memory.

3.1.4.2.2 Arduino Sketch

The Arduino IDE uses Arduino Sketch, a simplified variation of C/C++. While Arduino Sketch supports the object-oriented features of C++, its main focus for its design is to make hardware interaction easier for rapid development. Arduino Sketch is highly beneficial for quick testing of sensors, actuators, and communication modules, making this language very useful for the early prototyping stages in the EASE project.

3.1.4.2.3 C

C is a simple programming language that is commonly used for low-level programming, such as in cases for Code Composer Studio and STM32Cube. This use of the programming language does not have a lot of object-oriented components involved, and instead is mainly used for hardware development and is very popular for embedded and semiconductor programming. The C programming language has many open libraries for simplified and advanced functions to help to overall programming experience. The C programming language is also particularly good for hardware because it allows the user to get easier access to their hardware's memory through the language. The language allows for easy access to registers, memory and flags; therefore, it allows users to adjust memory in different hardware that is attached to a C program. The C programming language requires compilation so that it can translate high-level language to assembly and then machine code for the computer to execute certain memory operations. C is an older language meaning that it does not possess a lot of the new styles that would be preferred in a newer project with a large, high-level scope, but is still a preferred choice for low-level coding and can be easily be used for embedded software, which could be very useful for this project which involves a microcontroller.

3.1.4.3 Development Environment Summary

The table 3.1.4.3 compares the different development environments and highlights the preferred one in green. Because not many of the group members were directly writing code it was mainly up to our software developer and computer engineering group member on which development environment was preferred and that information will be compared with the hardware preferences for the MCU and the two outcomes align in a middle ground when parts are selected. The general advantages provided by Arduino IDE were great because we wanted a low power system which is Arduino IDE's ideal use case and for our hardware most of us are familiar with Arduino MCUs. The steeper learning curve of Arudino's Arduino IDE was also not as much an issue for our group because of our experience using it in our embedded systems class. The WICED Studio is another interesting IDE because of its wireless specialty, we have not worked with wireless RF MCUs before which makes any help towards that very enticing.

3.1.5 Battery / Power Supply

Due to the portable nature of our project, we will be using a battery to power our device. Some important variables to look at when researching a battery for this project are size, nominal output voltage, safety, and rechargeability. We would like to keep the size of the battery as small as possible to make the device as comfortable as possible for the user, although we will not be able to test the device for comfortability. As for nominal output voltage, the battery should be able to power the MCU, along with all the necessary sensors and transmitters that are needed to provide the data we are collecting. It should also be able to last as long as the user needs to use the device, which we have estimated to be as long as 7 days. Safety is an important factor due to the explosive nature of some types of batteries when used improperly. They should also be non-toxic and safe for

contact with skin as a necessary precaution. Since one of our specifications for this project is to make the product reusable, we would also like for the battery to either be low cost to the user or rechargeable.

IDE / Language	Arduino IDE & Arduino Sketch (Selected)	Code Composer Studio & C	STM32Cub & C/C++	WICED Studio & C/C++
Target MCU	Arduino boards (various microcontrollers)	TI CC2640R2L (TI microcontrollers)	STM32 microcontrollers (STMicro)	CYW207 MCUs (Infineon)
Hardware Integration	General purpose; lacks low-level control	Direct integration with TI hardware	Designed for STM32 MCUs	Tailored for Bluetooth/Wi-Fi devices
RTOS Support	No built-in RTOS support	TI-RTOS integrated	FreeRTOS or STM32 RTOS supported	Basic RTOS support for connectivity
Programming Language	Arduino Sketch (C++ variant)	C (low-level, hardware-near programming)	C/C++ (object-oriented option)	C/C++ (standard for embedded systems)
Code Efficiency	Moderate efficiency, easy prototyping	High-efficiency, low-overhead	Moderate depends on usage of C++ features	Moderate complexity with focus on wireless apps
Ease of Use	Extremely easy for prototyping	Steeper learning curve but highly optimized for TI MCUs	Graphical interface simplifies peripheral setup	Moderate complexity with focus on wireless apps
Ideal For	Rapid prototyping, simple projects	Low-power, embedded systems with tight hardware control	General embedded system, moderate power needs	Wireless (Bluetooth/Wi-Fi) devices

Table 3.1.4.3 Comparison of Development Environments

3.1.5.1 Types of Batteries

Understanding the different types of batteries is crucial when designing or selecting electronic devices, as the choice of battery directly impacts performance, longevity, and safety. Each battery type—such as lithium-ion, nickel-metal hydride, or alkaline—offers unique characteristics including energy density, rechargeability, cost, and environmental impact. Choosing the right battery ensures that the device operates efficiently and meets

its intended purpose, whether it's powering a small sensor or a portable electronic system. Proper battery selection also contributes to sustainability, user convenience, and the overall success of the electronic product.

3.1.5.1.1 Lithium Ion

The two most common rechargeable batteries that are on the market currently are lithium-ion and nickel-metal hydride batteries. Lithium-ion batteries are the batteries that are found in smartphones, hobby electronics, laptops, etc. These batteries typically operate at around 3.7 volts per cell. This operating voltage is higher than most other accessible batteries, which is a huge advantage as less batteries would have to be used to power the device.

They also come in many different sizes, which would be useful for this project as we are trying to keep the battery as small as possible. Although the batteries are rechargeable, there is a risk of the battery exploding if not charged or discharged properly. Battery protection circuitry would have to be considered and implemented in our device, if lithium ion batteries are used. This could add unnecessary size and risk to our product.

3.1.5.1.2 Nickel-Metal Hydride

Another common rechargeable battery is nickel-metal hydride (NiMH) batteries. They are typically found in toys, flashlights, cordless tools, etc. Compared to other types of rechargeable batteries, NiMH batteries have a high energy density, though not as high of an energy density as lithium ion batteries. They are also a more affordable and environmentally friendly battery technology compared to other rechargeable batteries, including lithium ion batteries. One drawback of using NiMH batteries is they are prone to voltage depression if not charged properly. Voltage depression is when a battery has a lower discharge voltage than expected. This occurs when the battery is repeatedly charged before fully discharging or when it is not charged to its full capacity. This would be less user friendly and potentially shorten the device's lifespan [\[20\]](#).

3.1.5.1.3 Lithium Coin Cell Batteries

Coin cell batteries are small coin shaped batteries that are typically found in watches, remote controls, calculators, key fobs, hearing aids, thermometers, toys, musical greeting cards, etc. The advantage of using these types of batteries is primarily their size. They are typically around 20 mm in diameter by 3.2 mm thick. Button batteries made of lithium output a voltage between 3-3.6V. Should we need a higher voltage, we can just stack them to make them in series. They are also inexpensive and accessible to anyone. As these batteries are not rechargeable, they would have to be replaced by the user. Another disadvantage is the high internal resistance, which leads to a limited current draw. Although the high internal resistance is a disadvantage, it can also be seen as an advantage because they are also safer. To use these batteries, we would need to use a special holder, which is also something to consider [\[21\]](#).

3.1.5.1.4 Alkaline Batteries

The most common type of disposable battery is alkaline batteries. These are the typical AAA or AA batteries that you can find in pretty much any device that uses disposable batteries. These batteries are a safer option compared to the rechargeable batteries. They typically output ~1.5V, which is insufficient on its own to power an MCU and the necessary peripherals. If we were to use alkaline batteries to power our device, we would have to use at least 2 batteries in series to obtain the necessary voltage. This would significantly increase the size of our device, which we are trying to minimize. Another disadvantage is these batteries are not rechargeable.

3.1.5.1.5 Battery Summary

The decision for which battery type to choose falls mostly on the categories of safety and size. Those attributes are the most important to us for this project. The coin cell battery is preferable here because of its small size and its safety. Other options we had considered were small lithium ion batteries but couldn't justify the safety risk. The table 3.1.5.2 outlines the characteristics we looked for and compared the battery types with, highlighted in green is the choice we believe to be the most preferable. NiMH batteries were also a decent consideration but lack power density the lithium coin cell and lithium ion batteries have which would hurt our project. If we were to use a very power hungry sensor solution we would not be able to accommodate it with a NiMH battery most likely. In the future when we do more testing I think it's important to note that this decision could easily change. Using an RTOS low power MCU and low power sensing option we could justify the use of a different battery type like a NiMH battery. This would require us to most likely alter our voltage regulation method or design but wouldn't be very hard to implement beyond that.

	Attribute			
Type of Battery	Size	Safety	Rechargeable	Output Voltage
Lithium Ion	Varies	Prone to exploding if not handled correctly	Yes	3.7V / cell
NiMH	Varies	Generally safe	Yes	1.2V
Coin Cell	Ø 20 mm x 3.2 mm	Safe	No	3-3.6V
Alkaline	Varies	Safe	No	1.5V
9V	21,443 mm ³	Safe	No	9V

Table 3.1.5.2 Comparing Types of Batteries

Although the ideal solution, implementing the design changes of hardware V2 and hardware V3 as described in Chapter 6 found that the coin cell battery was unable to deliver the current demand of 150 mA, with full system integration and bluetooth connection. Because of this, the battery of the prototyped design was changed to a 9V battery, to ensure that the power supply was capable of meeting the expected load demand. Due to its size and limited duration, the 9V battery should not be used as a definitive power source. Alternative power sources capable of meeting both the voltage and current demands should be considered for future designs.

3.1.6 PCB

Printed Circuit Boards (PCBs) are the backbone of modern electronic devices, providing the physical platform for mounting and electrically connecting electronic components. They replace bulky and error-prone wiring systems with compact, layered circuit patterns made from conductive pathways etched onto non-conductive substrates. PCBs enable precise, repeatable manufacturing of complex circuits and contribute to the reliability, miniaturization, and performance of everything from consumer gadgets to industrial equipment. Their design involves careful planning of layout, signal integrity, thermal management, and component placement, making them a critical aspect of any successful electronic system. Whether used in prototyping or mass production, PCBs are essential to turning electronic designs into functioning, real-world products.

3.1.6.1 Types of PCBs

The following sections outline the various types of PCBs, offering a comparison of which type is most suitable to meet the design specifications of this project.

3.1.6.1.1 Single Sided

The most basic and simplistic PCB is the single-sided PCB which places all components and circuitry onto one side. These PCBs are composed of a single conductive layer of copper above a substrate, typically FR-4 Polyimide (fiberglass-reinforced epoxy resin). Components are then soldered or mounted on one side of the board while the other side shows the etched circuit connecting the components. Due to its simplicity, single sided PCBs are extremely cost effective and easy to manufacture.

This type of PCB is used in applications with minimal complexity and component density and are typically used for circuit designs that do not require extensive routing or high-frequency capabilities. Thus, single sided PCBs can be used for simple circuit designs or prototyping due to its manufacturing efficiency [22].

3.1.6.1.2 Double Sided

Double sided PCBs can be used when circuit complexity increases but space and compactibility must be maintained. This type of PCB consists of conductive pathways on both sides of the circuit, allowing components to be placed on both sides, increasing

circuit complexity capability and component density while minimizing overall board size. Vias, plated through holes, allow for interconnections to exist between both sides, acting as conduits for electrical connections between both layers.

Additional steps are required when designing and manufacturing double sided PCBs such as alignment and registration. Due to its nature, double sided PCBs can include both surface mount components and through hole components which allow for a wider range of functionalities and applications. This PCB provides an increased balance between circuit intricacy and complexity with size and space efficiency.

3.1.6.1.3 Rigid

Most PCBs are typically rigid PCBs, made from solid, inflexible materials like FR-4 Fiberglass. The rigidity provides a stable platform for electrical component mounting, allowing for precise alignment and soldering of components. With the increased precision, rigid PCBs generally offer improved reliability, stability, and integrity of the circuit, especially when durability is a critical design consideration.

Rigid PCBs can support both simple and complex circuit designs while still maintaining compatibility. They can also accommodate multi-layer circuits, allowing for increased routing density and enhanced functionality. Furthermore, they offer good thermal and electrical performance making them suitable for circuits requiring high-frequency applications. However, rigid PCBs would not be suitable for designs which require significant bending and conforming to shapes.

3.1.6.1.4 Flexible

Designs requiring significant bend and conforming would require flexible PCBs. Made with a polymer substrate, typically polyimide or polyester, flexible PCBs offer significant bend and twist with thinner and more ergonomic designs while maintaining electrical performance in both static and dynamic electronic applications. These PCBs can be integrated with curved surfaces or tight spaces that typical PCBs would not be able to integrate with. Electrical reliability is maintained by reducing the number of interconnects within the circuits and allowing them to contour with the PCB which minimizes stress on the connections.

Polyimide, the PCB substrate, is highly resistant to heat, allowing it to be used in solder reflow cycles with little to no change in structure from expansion or contraction when exposed to temperature fluctuations. Thus, flexible circuits that require soldering typically necessitate a polyamide substrate. A polyester (PET) substrate is not heat resistant and thus can only be used for solderless circuits. Electrical connections can be made with crude pressure with an isotropic conductive elastomer.

Rather than use a solder mask like typical PCBs, flexible PCBs use an additional PI, PET, or flexible solder mask ink films as a overlay instead to provide insulation to the outer surface conductors, provide protection from corrosion and damage. PI and PET films are

typically $\frac{1}{3}$ mil to 3 mils in thickness and glass fiber and epoxy substrates are typically 2 mils to 4 mils in thickness.

The application of the PCB will dictate the type of conductor that is used within it. For static applications with minimal movement, twist, and flex, the typical laminated electro deposited copper foil typically found in rigid PCBs can still be used. This will help maintain high current carrying conductors at the minimum viable width. However, for applications requiring repeated creasing and movement, standard copper foil conductors would be a poor choice due to the fatigue and stress placed upon it. Instead, higher grade rolled annealed (RA) foils should be used as the annealing process elongates the grain structure of the copper, allowing for more stretch before cracking from fatigue occurs. However, the higher grade rolled annealed foil significantly increases cost.

Specially developed adhesives connecting the copper foil to the PI films are used as the annealed copper foil does not possess enough grip compared to FR-4 typically found in rigid PCBs. Single and double sided copper-clad films can be pre-laminated for circuit etching with acrylic or epoxy-based adhesives approximately $\frac{1}{2}$ to 1 mil thick to maintain flexion. Mechanical reinforcement is also implemented in the form of silicones, hot-melt glues, and epoxy resins at the section joining the flex and rigid interfaces. These offer protection to the fulcrum of these points, minimizing fatigue, crack, and tear from repeated flexion.

Material selection is an important consideration when designing a product, especially for flexible PCBs which can fail under various conditions depending on its composition. Material properties will dictate the mechanical design, evaluation, and testing of the product under various conditions and will determine the reliability and bending radius. For the purposes of this project, the material composition must be resilient to movement, sweating, and bodily fluid [23],[24]. The figure below provides an illustration of a cutaway view of a single-layer flex PCB.

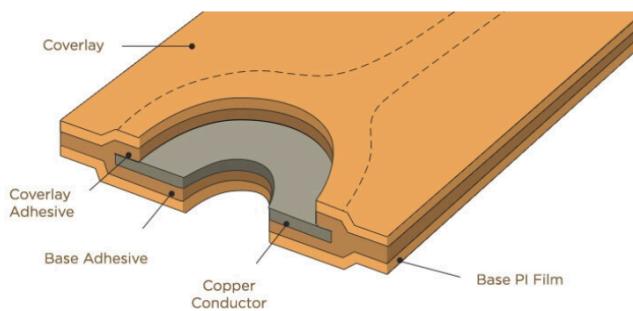


Figure 3.1.6.1.4 Flex PCB Cross Section (reprinted with permission from Altium)

3.1.6.1.5 Rigid-Flex

Combining attributes, rigid-flex PCBs offer a compromise for circuits that require both stability and flexibility. Rigid-flex PCBs are composed of multiple layers of rigid and flexible substrates that allows the PCB to maintain structural integrity in certain areas

while allowing bend and twist in other areas. Similar to flex PCBs, rigid-flex is typically implemented in design situations with space constraints and critical component densities. By integrating both, rigid-flex can accommodate complex routing and component placement.

The primary advantage of rigid-flex PCBs is their ability to improve and enhance reliability while reducing the number of required interconnects between the rigid sections and the flexible sections. With this advantage, the PCB reduces potential points of failure making it suitable for environments subjected to movement and mechanical stress. However, the intricacy and complexity associated with rigid-flex PCBs is significantly more costly compared to traditional rigid PCBs as well as flexible PCBs.

3.1.6.1.6 Multilayer

Multilayer PCBs are typically composed of three or more layers that allow for significantly greater complex circuit designs and component density. Multiple layers of both conductive and insulating materials, stacked and bonded through lamination, allow for intricate electrical routing making them optimal for sophisticated applications with limited space. The additional layers can integrate numerous components and functions that accommodate for power distribution, signal integrity, and ground planes. Unfortunately, manufacturing of such PCBs is significantly more difficult as it requires layer alignment, via plating, and precision control during fabrication.

With this type of PCB, special considerations have to be made to improve electromagnetic compatibility. For fewer layers (typically four layer stacks) this involves positioning the signal layers close to the power and ground planes while placing a thick core between them. This creates a tight coupling between the signal traces while the ground plane helps reduce plane impedance. For larger stacks (typically twelve layer stacks), thinner dielectric materials are required which naturally create the tight coupling between layers [\[25\]](#).

3.1.6.1.7 Aluminum

Aluminum PCBs have the same structure as most basic PCBs (single sided and double sided) but utilizes a metal substrate and aluminum core. This feature primarily provides the unique advantage of superior thermal management compared to standard traditional PCBs. The aluminum substrate dissipates heat that gets generated from high-power components and is thus generally used in applications where heat management is critical such as LED lighting, power supplies, and high frequency devices. The thermal conductivity of aluminum PCBs enhance electrical performance and longevity of components by transferring heat away from temperature sensitive parts. Additionally, their rigid structure provides increased mechanical stability relative to standard PCBs.

Aluminum PCBs are structured with four layers: copper foil layer, dielectric layer, aluminum base, and aluminum base membrane layer. The copper layer is typically thicker for a larger current carrying capacity. The dielectric layer is approximately 50 µm to 200

μm thick, acting as a thermally conductive layer with low thermal resistance. The aluminum base is the aluminum substrate with high thermal conductivity, with the membrane acting as a protective layer against unwanted scratching or etching. The figure below depicts the structure described.

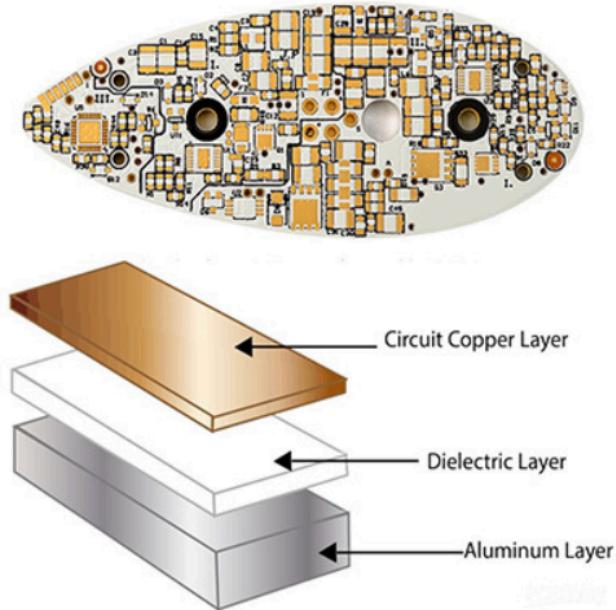


Figure 3.1.6.1.7 Aluminium Substrate Diagram (from AllPCB)

3.1.6.1.8 High-Density Interconnect

For circuits requiring a high number of components and connections in a compact space, high-density interconnect (HDI) PCBs are used. This type of PCB can integrate multiple layers into a very thin board and utilizes both microvias and buried vias, which are significantly smaller than traditional vias, in unique configurations including stacked, staggered, and through hole vias, to minimize space. The primary advantage of HDI PCBs is their ability to support high speed signal transmission while minimizing crosstalk, the transfer of unwanted signals between communication channels. HDI PCBs utilize smaller trace widths and spacing that facilitates denser circuit layouts to preserve signal integrity. They can also incorporate blind and buried vias to further enhance flexibility when routing electricity while also reducing layer count. The benefits of performance, size reduction, and design versatility come with an increased manufacturing cost [\[26\]](#).

3.1.6.2 PCB Attribute Selection

The following table provides a comparison of the various PCB technologies. Selection of technology was based on its capability for circuit complexity, cost, and its unique attributes. For the purposes of this project, a PCB with high degrees of flexion and malleability is required to meet the physical demands of the device. Thus, flexible PCB was selected as the chosen technology (highlighted in green).

	Circuit Complexity	Cost	Unique Attribute
Single	Low	Low	-
Double	Medium	Low	-
Rigid	-	Low	Increased stability and durability
Flex	-	Medium	Allows significant flexion
Rigid-Flex	-	High	Allows some flexion while maintaining some stability
Multilayer	High	High	High compactness and complexity
Aluminum	-	High	Thermal management
High Density Interconnect	High	High	Extremely high compactness and complexity

Table 3.1.6.2 PCB Comparison

3.1.7 Voltage Regulation

As batteries start discharging, their output voltages can start to fluctuate, while MCUs and other peripherals require a stable voltage to operate effectively. This is where a voltage regulator comes in. The voltage regulator ensures the MCU receives the correct and stable voltage, regardless of voltage fluctuation.

They can also help with undervoltage handling, which means when the battery's voltage level drops below the required voltage, the voltage regulator can step it up to maintain proper functionality. There are two main types of voltage regulators: linear regulators and switching regulators.

3.1.7.1 Types of Voltage Regulators

The following sections outline the various types of voltage regulators, offering a comparison of which type is most suitable to meet the design specifications of this project.

3.1.7.1.1 Linear Regulators

The first type of voltage regulator that we will be examining is the linear voltage regulator. This voltage regulator is the simpler of the two, as it only requires a couple of

capacitors and resistors to work. The simplicity of the linear voltage regulator decreases cost and makes it easier to design and implement.

To regulate the voltage, linear regulators use an active pass device controlled by a high-gain operational amplifier. The drawback to using a linear voltage regulator is it can only output a voltage that is less than the source. This leads to a lower efficiency compared to switching regulators. The power lost is typically dissipated as heat, meaning you would have to provide active or passive cooling to prevent damage to the regulator or surrounding components [27].

3.1.7.1.1 Linear Regulator Topologies

The most common topology for a linear regulator is a low-dropout (LDO) regulator. These voltage regulators work best when there is a small difference between the input and output voltage. LDOs are best suited for low-power applications where simplicity and low noise are priorities [28].

3.1.7.1.2 Switching Regulators

Unlike linear regulators, switching voltage regulators can either be step-up or step-down converters, which makes them more versatile than linear regulators. This means they can output a voltage higher than the input. Some benefits of using a switching regulator are they have better thermal performance, higher efficiency, and can help keep a higher current.

These regulators are not as simple as linear voltage regulators, as they require more components to operate. Another drawback is they create a lot of electrical noise, due to the high frequency switching. Switching regulators are best suited for high power, high efficiency applications, especially when the output differs significantly from the input.

3.1.7.1.2.1 Switching Regulator Topologies

The first switching regulator topology we will examine is the buck (step-down) converter. This regulator is used when the input is higher than the output voltage. Compared to linear voltage regulators, they have a higher efficiency and better thermal performance and work much better when the input voltage is much higher than the output voltage.

The next switching regulator topology is a boost (step-up) converter. This regulator outputs a higher voltage compared to the input by storing energy in an inductor then releasing it to the load. It is useful in battery powered devices, when the battery's output voltage is less than the voltage necessary.

The final switching regulator topology is a buck-boost converter. This switching regulator can perform both functions that buck and boost converters can perform. They provide a versatile option when the input voltage fluctuates above and below the required voltage.

It is also useful in battery powered devices when the battery's voltage fluctuates over time as it discharges.

3.1.7.3 Voltage Regulator Summary

The decision for what voltage regulator technology to use depends on a few other variables such as MCU supply voltage requirements and battery supply voltage but the table 3.1.7.1.3 outlines the characteristics we are most interested in when comparing the regulator types. These characteristics for the most part can give us a good understanding of what we would want to use.

The preferred regulator for us would be a switching regulator due to its efficiency and low heat output. The boost converter would be ideal for any battery choice which outputs below the power supply value we want to have on the board. Most MCUs have their own internal DC-DC voltage regulator for internal logic which makes this mostly a sensor voltage supply question. The boost converter is ideal for us then mostly because of our sensing types.

	Linear	Switching Regulators		
Specifications	LDO	Buck	Boost	Buck-Boost
Efficiency	Moderate (60-90%)	High (up to 95%)	High (up to 95%)	High (up to 95%)
Heat	Moderate	Low	Low	Low
Step-up or Step-down	Step-down	Step-down	Step-up	Both
Complexity	Simple	Complex	Complex	Complex

Table 3.1.7.3.1 Voltage Regulator Type Comparison

Although the ideal solution, implementing the design changes of hardware V2 and hardware V3 as described in Chapter 6 found that an LDO was better suited for the demands of the design. Thus, this type of linear voltage regulator was implemented instead.

3.2 Part Selection

After researching the various technologies required to implement this design, specific parts and their corresponding manufacturers must be researched and identified to meet both the design requirements and real-world constraints of our project. This is presented in the following sections.

3.2.1 MCU

As discussed in the 3.1 section regarding the MCU we wanted to choose an RF MCU because of its impact on our devices size and its benefit towards design ease. Of the three RF MCU manufacturers we looked at, two originally stood out as possible candidates because of developer support and features, these being Texas Instruments and STMicroelectronics. The comparisons in the 3.1 can be used again when deciding on a specific part but with the device as a whole in mind. We took a look at more MCUs from each manufacturer as the previous ones were mentioned and researched to understand more about the models, development support, and manufacturers, not the MCUs themselves.

As a recap there was a list of traits we prefer in an MCU: we want a small package size (VQFN, CSP, BGA), GPIO pin count that can support any sensor application/type we choose (Solid State sensor needs the most at around 14 GPIO pins), reliability (good IP rating if applicable), compatibility with our PCB type (already determined during the research of package types), and cost effective. Unfortunately IP rating isn't normally given for MCUs and cannot be found on the datasheet but we can use what we know about packages to infer.

After testing we determined that this list of traits needed to change in order to deliver a working proof of concept. GPIO count was still valuable to us but size was no longer an issue. We instead needed to find an MCU or MCU module that would work consistently and could be easily integrated into any design. This means extra preference was placed on bonus peripherals, ease of implementation, and documentation support.

3.2.1.1 Texas Instruments CC2640R2LRHBR

The CC2640R2RHBR is an MCU produced by Texas Instruments in the CC2640R2L product category. This RF MCU is equipped with an Arm Cortex M3, 275KB flash memory, 28KB or SRAM, and a 2.4 GHz RF transceiver that is compatible with Bluetooth LE 5.1. The RHBR variant is the 32 pin variant VQFN package with 15 GPIOs whereas the RGZR variant is the slightly larger 48 pin VQFN with 31 GPIOs. These devices use a developer platform that the group is comfortable with and are produced by a manufacturer that the group is comfortable with making it a good option from the gate. This MCU is pin compatible with SimpleLink for the CC2640, CC2642R, and CC1350 in select packages [\[29\]](#).

3.2.1.2 Texas Instruments CC2652R1FRGZR

The CC2652R1FRGZR is an MCU produced by Texas Instruments in the CC2652R product category. These RF MCUs use a 48MHz Arm Cortex M4F, have 352KB of flash memory, 80KB of SRAM, and a 2.4 GHz RF transceiver that is compatible with Bluetooth LE 5.2 [\[30\]](#). Again the naming convention applied to the previously mentioned Texas Instruments MCU applies here aswell, the larger 48 pin VQFN with 31 GPIOs is the RGZ variant and is the only package size available for this MCU line.

3.2.1.3 Texas Instruments CC2540F256RHAR

The CC2540F256RHAR is an MCU produced by Texas Instruments in the CC2540 product category. These RF MCUs use 8051 Core with 128KB or 256KB flash memory, 8KB of SRAM, and come in only one package size, the 40 pin QFN with 21 GPIOs [\[31\]](#). The 2.4GHz radio transceiver works with Bluetooth LE 4.0. It's very similar to the CC2640 MCU just like the previous MCU and is just from a previous generation.

3.2.1.4 STM STM32WL33C8V6

The STM32WL33C8V6 is an RF MCU produced by STMicroelectronics. These MCUs use a 32 bit Arm Cortex M0+, have up to 256KB flash memory, 32KB SRAM, and 159-185 MHZ, 413-479 MHz, 826-958 MHz frequency band options [\[32\]](#). Bluetooth is not an option for this MCU which is unfortunate but good to know. These MCUs are offered in two package sizes, the 48 pin VFQFPN with 32 GPIOs and the 32 pin VFQFPN with 17 GPIOs.

3.2.1.5 STM STM32WB55CGU6

The STM32WB55CBU6 is an RF MCU produced by STMicroelectronics. This MCU uses a 32 bit Arm Cortex M4, up to 1MB flash memory, up to 256KB SRAM, and a 2.4GHz RF transceiver that uses Bluetooth 5.3 [\[33\]](#). The varying flash and SRAM sizes are due to the differing variants that can be purchased. The variants also have different package sizes of a 48 pin UFQFPN, 68 pin VFQFPN, 100 pin WLCSP, and 129 pin UFBGA. Up to 72 GPIOs depending on the package type with the largest package being only 8x8 mm.

3.2.1.6 STM STM32WLE5CBU6

The STM32WLE5CBU6 is an RF MCU produced by STMicroelectronics. This MCU uses a 32 bit Arm Cortex M4, with 256KB of flash memory and 64KB of SRAM. It has a frequency range of 150MHz, to 960MHz and is compatible with LoRaWAN® Spec v1.0 [\[34\]](#). While this isn't Bluetooth it is a possible communication protocol that we could potentially. I believe our project is better suited towards the higher frequency bluetooth platform because of the better support and exposure the team has to it. This MCU comes in a 48 pin UFQFPN, a 59 pin WLCSP, and a 73 pin UFBGA, with up to 43 GPIOs.

3.2.1.7 ESP32 WROOM Module

The ESP32 WROOM module is RF capable and produced by espressif. This module differs from other MCUs on this list in the fact that it is a module. This means that peripherals such as PCB antenna, crystal oscillators for RF transmission, and processing CPU are all included within the module. The internal is a 32-bit 240 Mhz processor with 520 KB of SRAM. Included in the module that we will take advantage of are the 2MHz crystal oscillator for BLE and the PCB antenna. The larger package size was discredited

after initial testing proved we needed to prioritize ease of integration first for early prototypes and proof of concept. The large amount of gpios fits our use case making the ESP32 WROOM module a good fit.

3.2.1.8 Picking an MCU

The choice for the MCU is not the most convoluted or critical decision when all the variables have been weighed and the most important ones have defined your search. Out of only 2 manufacturers only roughly 10 total MCUs were available to compare and we compared 6 of them. For the reasons of cheaper cost, good package sizes, and bluetooth compatibility the choice went to the CC2640R2RHBR. The other options with larger sizes with much larger GPIO counts sound nice but are overkill and will just be unreasonable.

The CC2540 originally sounded like a great option because of how cheap it was and the package size is not very much larger but like I said the extra GPIOs are not needed and we need to save space at all costs. The other smaller packages like the STM WLCSP that had an area of only (4.4x4.4 mm) sounds like a good idea but those packages aren't the most reliable or protected and we want a more sturdy package size so it has no chance of breaking.

Another big reason is comfortability, our group knows TI MCUs from previous classes and is familiar with their development environment and documentation. After testing and determining that the issue of size needed to be placed behind the issue of ease of integration we decided to switch to the ESP32 WROOM module instead. This MCU module, while being quite larger than our original choice the CC2640, included integrated external oscillators and a PCB antenna, eliminating the need for a transmission circuit. Table 3.2.1.8 outlines the chosen selection and the criteria used when making the decision.

3.2.2 Sensor

The sensor is a very vital part of the project. Our project's success rests on the ability of this sensor to reliably and accurately determine how used or full the menstrual pad is and communicate this back to the MCU or transmitter. A sensor that does what we are looking for doesn't exist yet and the core of our project is the design of such a sensor. During our research of possible sensors and sensor types there were a few that showed some promise of how we might want to design our sensor and we can compare those types.

3.2.2.1 Capacitance Sensors

Capacitance sensors could be useful for a number of reasons such as their size, versatility, and ease of implementation. Because the capacitance sensor only needs to compare its results against a changing dielectric constant it could potentially be embedded in the pad like a traditional soil moisture sensor and give us good data. The problem with these

	CC2640 R2L	CC2652 R	CC254 0	STM32W L33	STM32 WB55	STM32 WLE5	ESP32W ROOM
Cost	\$4.17	\$6.21	\$3.34	\$5.11	\$5.23	\$7.62	\$6.95
Package s	VQFN32 (5x5 mm) and VQFN48 (7x7 mm)	VQFN48 (7x7 mm)	VQFN40 (6x6 mm)	VFQFPN48(6x6 mm) VFQFPN32(5x5 mm)	UFQFPN48 (7x7 mm) VFQFPN68 (8x8 mm) WLCSP100 (4.4x4.4 mm) UFBGA129 (7x7 mm)	UFQFPN48 (7x7 mm) UFBGA73 (5x5 mm)	(25.5x18 mm)
GPIO Count	15 and 31	31	21	32 and 17	30,49,72 , 72	29 and 43	32
Bluetooth Compatible	Yes	Yes	Yes	No	Yes	No	Yes

Table 3.2.1.8 MCU Comparison

sensors is that they are continuous, varied, and less accurate than other sensors. Continuous measurements are normally a good thing but are bad in this case because the sensor is going to be introduced to a large amount of movement and change which may skew data [35].

3.2.2.2 Pressure Sensors

Pressure sensors, more specifically the hydrostatic and thin film pressure sensors could also prove to be useful in our design of a new sensor application. If we can design a thin film pressure sensor that can accurately determine the pad's capacity using a pressure value formed from the thin film pressure sensor we can possibly get something that is implementable in our design. The issue again with this is the variable change from having

a sensor that relies on physical change in an environment where it will be moving brings reliability and accuracy issues.

3.2.2.3 Solid State Sensors

Solid state sensors show the most promise because they are adaptable. Solid state sensors can be used discretely which means they are much less susceptible to the challenges the other sensors face due to the movement of the device and its environmental change. It could be combined with other sensor types as well such as the thin film or capacitance sensor and this could give us a way to have each sensor “check” the other sensor and give us potentially much more accurate data to work with. An example product here gives a better picture on how one would work [\[36\]](#).

3.2.2.4 Sensor Pick Summary

Ultimately the decision to pick a sensor comes down to which sensor type is most practical for our design and which sensor type is the most versatile. We needed a sensor type that can be easily adaptable to a small environment, isn't too large, and can still produce accurate results which is why we chose two sensor types in the hope that using both types can potentially increase our accuracy and reduce the variable affect the environment our device will be in has on the sensor. The use of capacitance and solid state sensors was the best choice here because they both are implementable at a small scale and can provide accurate results in a dynamic environment. Table 3.2.2.4 outlines the chosen selection and the criteria used when making the decision.

	Size	Accuracy	Versatility
Capacitance	Small	Average in a static environment compared to other popular options.	High, can be implementable at a small scale and usable in dynamic environments.
Pressure	Large, generally constrained by the pressure sensor housing.	High when in a static environment. Low when in a dynamic environment.	Low, generally needs to be used only in a static environment.
Solid State	Small	Average in both static and dynamic environments.	High. Performs average in both static and dynamic environments.

Table 3.2.2.4 Sensor Comparison

3.2.3 Capacitance to Digital Converter

To resolve the issue of low accuracy presented by capacitive sensors, our team decided to utilize a capacitance to digital converter (CDC) which allows us to detect the small changes in capacitance expected from our device and convert them into a digital signal for processing. Utilizing a CDC will provide high-resolution, low noise measurements of capacitance with close to femtofarad precision which can be easily integrated with an MCU through I²C or SPI. This IC will allow us to easily detect the mL changes within the hygiene pad with relatively high precision to meet the engineering specifications of the project.

3.2.3.1 Texas Instruments - FDC1004

The Texas Instruments FDC1004 is a high-resolution CDC designed for precise capacitive sensing applications with 16 bit resolution. It features four differential or single-ended input channels, allowing for flexible sensor configurations and multi-sensor measurements. With high sensitivity and femtofarad (fF) resolution, the FDC1004 is ideal for applications like liquid level sensing, proximity detection, and humidity measurement. One of its key attributes is built-in shielding technology, which reduces interference from environmental noise and parasitic capacitance, enhancing measurement stability. The device operates over an I²C interface, simplifying integration with microcontrollers while maintaining low power consumption, making it suitable for battery-powered and wearable applications. Additionally, the FDC1004 supports automatic offset and environmental compensation, ensuring reliable performance across varying conditions.

3.2.3.2 Analog Devices - AD7746

The Analog Devices AD7746 is a high-precision 24-bit Capacitance-to-Digital Converter (CDC) designed for ultra-sensitive capacitive sensing applications. It features one differential and two single-ended capacitance measurement channels, with an impressive resolution down to femtofarad (fF) levels, making it ideal for liquid level sensing, biomedical monitoring, and industrial applications. The AD7746 offers excellent noise immunity and high linearity, ensuring stable and accurate measurements even in challenging environments. It includes an on-chip temperature sensor for compensation, allowing for consistent performance across varying temperatures. With a standard I²C interface, it easily integrates with microcontrollers and embedded systems. The device operates at low power, also making it suitable for portable and battery-powered applications, while its ability to measure changes in dielectric properties enables advanced sensing solutions beyond traditional methods.

3.2.3.3 Texas Instruments- FDC2214

The FDC2214 from Texas Instruments is a high-resolution CDC designed for capacitive sensing applications. This 4-channel device offers industry-leading sensitivity by utilizing

resonant impedance sensing, making it ideal for proximity sensing, liquid level sensing, and material analysis. The FDC2214 operates over an I²C interface and supports a wide range of capacitance values, from pF to nF, enabling precision measurements in various environments. Attributes include low power consumption, high resolution, and capability to work with large capacitance ranges. However, setup for this IC can be slightly more complex and can be subject to noise issues.

3.2.3.4 Analog Devices- AD7156

The AD7156 from Analog Devices is a high-performance CDC designed for proximity sensing and touch applications. It features dual-channel capacitance measurement with adaptive threshold levels, providing high sensitivity and noise immunity. Operating on a low-power architecture, the AD7156 is well-suited for battery-powered applications such as portable electronics, industrial automation, and security systems. It supports an I²C-compatible interface for easy integration with microcontrollers and digital systems. Despite the lower power consumption, this IC is only capable of 12-bit resolution making it poorly suited for ultra-high precision applications.

3.2.3.5 Component Selection

Table 3.2.3.5 presents a summary of the possible CDC IC's to consider. Due to the scope and nature of the project, an IC with high-resolution should be prioritized. Although other attributes such as interface, temperature compensation, and power consumption are also important, each IC presented is equally comparable across these metrics. Thus, the TI FDC2214 should be selected. However, due to expected delays in shipping of the required adapters for breadboarding, the ADI AD7746 was selected instead.

3.2.4 Transmitter / Communication Module

3.2.4.1 RN 4871 by Microchip

The RN4871 Bluetooth Low Energy module by microchip has a small form factor that would be easy to implement into our device. The module measures at 9 x 11.5 x 2.1 mm. It interfaces with the MCU through a standard UART interface. It also comes with a built-in antenna, which would reduce the need for a separate antenna on the PCB. Its pre-certification for regulatory compliance (FCC, IC, CE) reduces development time, making it a versatile choice for compact, low-power wireless applications [\[37\]](#).

3.2.4.2 nRF52840 Bluetooth Low Energy Module by Nordic

The nRF52840 Bluetooth Low Energy module by Nordic has multiple ways of interfacing with the MCU. This module supports GPIO, SPI, UART, I2C, and USB interfaces for connecting peripherals and sensors. This gives us more freedom with our microcontroller as it can use any of the mentioned communication protocols. In addition to BLE, it also supports other wireless protocols such as Thread, Zigbee, and ANT. To power this module, it requires a voltage between 1.7-5.5V [\[38\]](#).

Parameter	TI FDC1004	ADI AD7746	TI FDC2214	ADI AD7156
Resolution	16-bit	24-bit	28-bit	12-bit
Capacitance Range	±15 pF	±4 pF	Up to 250 pF	Auto-calibrated
Baseline	0 to 100 pF	0 to 17 pF	N/A	
Channels	4	1 differential / 2 single-ended	4	2
Conversion Rate	100 samples / sec	45 Hz	High-Speed	Fast
Temperature Compensation	✓	✓	✓	✓
Power Consumption	Low	Medium	Medium	Low

Table 3.2.3.5 Capacitance to Digital Converter Part Comparison

3.2.4.3 nRF52832 Bluetooth Low Energy Module by Nordic

The nRF52832 Bluetooth Low Energy Module by Nordic supports SPI, UART, and I2C to interface with the MCU. The module supports Bluetooth 5.0, enabling longer range and faster data transfer while maintaining low energy consumption, making it ideal for wearable, IoT, and battery-operated devices. This module measures in at 16 x 10 x 2.2mm and takes a supply voltage between 1.7-3.6V. With a small form factor and ultra-low power consumption, it is widely used in compact, low-power wireless applications [39].

3.2.4.4 nRF51822 Bluetooth Low Energy Module by Nordic

The nRF51822 Bluetooth Low Energy Module is another BLE module by Nordic Semiconductors. It supports UART, I2C, and SPI to interface with a microcontroller. Its low energy consumption makes it well-suited for battery-operated devices, including wearables, beacons, and smart home applications. This module also contains its own antenna, which speeds up development time. It requires 1.8-3.6V to power it and measures at 18 x 10 x 2.9mm [40].

3.2.4.6 Picking a Communication Module

Although we have decided to go with an MCU that has Bluetooth built-in, should we need a Bluetooth Low Energy module separately, we have decided to pick the nRF52840 by Nordic Semiconductors. Its low power requirements make it a great selection for this

device because we will be running it off of a battery. It also supports UART, I2C, and SPI, which makes it a versatile module, as we are not limited to just UART with the RN 4871. Although the price is not the lowest of the 4 modules, it is still comparable to the prices of the other modules. Its size is also the smallest of the 3 Nordic BLE modules, making it a great option as we are trying to minimize size. Table 3.2.3.6 highlights the characteristics we used to base our decision and highlights our preferred choice.

	Attributes				
Module	Size	Communication Protocols	Power Requirements	Other Features	Price
RN 4871	9 x 11.5 x 2.1 mm	UART	1.9-3.6V	None	\$9.24
nRF52840	15.5 x 10.5 x 2.1 mm	UART, I2C, SPI	1.7-5.5V	NFC	\$8.50
nRF52832	16 x 10 x 2.2 mm	UART, I2C, SPI	1.7-3.6V	NFC	\$9.95
nRF51822	18 x 10 x 2.9 mm	UART, I2C, SPI	1.8-3.6V	None	\$7.95

Table 3.2.4.6 RF Communication Module Comparison

3.2.5 UART to USB Bridge

A UART to USB bridge IC is a specialized integrated circuit that enables communication between a device using a Universal Asynchronous Receiver/Transmitter (UART) interface and a USB-equipped host, such as a computer. These ICs serve as a crucial link for microcontrollers and other embedded systems that lack native USB connectivity, allowing them to interface with modern devices for tasks like programming, debugging, or serial data communication. The bridge IC converts UART signals—typically simple TX and RX lines—into USB signals, handling the USB protocol internally and often presenting itself as a virtual COM port on the host system. Widely used examples include the FTDI FT232R, Silicon Labs CP2102, and CH340 series, which offer robust driver support, adjustable baud rates, and optional flow control, making them a reliable and convenient solution for serial-to-USB conversion in embedded designs.

3.2.5.1 Microchip MCP2221A

The Microchip MCP2221A is a versatile USB-to-UART bridge IC that also includes additional GPIO pins, I²C, and ADC functionality, making it more than just a simple serial bridge. It connects microcontrollers or other UART-enabled devices to a PC via

USB, presenting itself as a virtual COM port. What sets the MCP2221A apart is its support for I²C communication and up to four GPIO pins that can be configured for various digital functions or analog input. With built-in clock generation and minimal external components needed, it simplifies PCB layout and system integration. It's supported by Microchip's utility software and libraries, making it easy to configure and use for embedded applications, sensor interfacing, or development tools.

3.2.5.2 Silicon Labs CP2102

The Silicon Labs CP2102 is a widely-used USB-to-UART bridge IC known for its simplicity and reliability. It supports full-speed USB 2.0 communication and provides a straightforward way to add USB connectivity to embedded systems that rely on UART. The chip integrates a USB transceiver, oscillator, EEPROM, and voltage regulator, minimizing the need for external components. It offers robust driver support across Windows, macOS, and Linux, and is commonly found in commercial devices and development boards. Its compact footprint and ease of implementation make it ideal for portable and cost-sensitive applications where consistent serial communication is needed.

3.2.5.3 FTDI FT230X

The FTDI FT230X is a compact and efficient USB-to-UART bridge IC designed for easy integration and low power consumption. It is part of FTDI's X-Chip series and supports USB 2.0 full-speed operation, with features such as configurable CBUS pins, USB battery charger detection, and a built-in clock generator. The FT230X presents itself as a standard virtual COM port and is supported by FTDI's well-established drivers, which are available for multiple operating systems. Its small package and minimal external components make it an excellent choice for space-constrained designs that need reliable USB-to-serial communication.

3.2.5.4 FTDI FT260

The FTDI FT260 is a more advanced USB bridge IC that supports both USB-to-UART and USB-to-HID (Human Interface Device) class communications. This makes it ideal for applications that require driverless operation on most platforms, as HID class devices are natively supported by operating systems without the need for additional drivers. In addition to UART, the FT260 provides I²C interface support and multiple GPIOs, giving designers flexibility in communicating with sensors, peripherals, or other microcontrollers. Its secure HID mode is useful in environments where virtual COM ports may be restricted. With its dual-interface support and robust feature set, the FT260 is suited for applications like configuration tools, industrial controllers, or secure communication interfaces.

3.2.5.5 IC Selection

The following table summarizes the attributes of each of the researched UART to USB Bridge IC's, offering a comparison between baud rate, voltage range, IC packaging, and

price. Ultimately, the CP2102 was selected as it is the recommended UART to USB Bridge IC for the ESP32-WROOM, with complete layout and integration within both datasheets and the ESP32 dev board.

	Microchip MCP2221A	Silicon Labs CP2102	FTDI FT230X	FTDI FT260
Baud Range	300-460800 bps	300-100000 bps	300-3000000 bps	1200-12000000 bps
Voltage Range	3.0 to 5.5V	3.0 to 5.25V	3.3 to 5.25V	1.8 to 3.3V
Package	TSSOP-14	QFN-28	SSOP-16	TSSOP-28
Price	\$2.53	\$5.59	\$2.26	\$1.99

Table 3.2.5.5 UART to USB Bridge Comparison

3.2.6 Battery / Power Supply

Selecting the right battery or power supply is crucial in any electronic design, as it directly affects the performance, reliability, and safety of the entire system. An improperly matched power source can lead to voltage drops, overheating, instability, or even permanent damage to components. Factors like voltage range, current capacity, battery chemistry, and efficiency all play a role in determining whether a power source can meet the demands of the device under both normal and peak load conditions. Additionally, considerations such as size, weight, rechargeability, and operational environment impact the practicality of the power solution, especially in portable or embedded systems. A well-chosen power supply ensures consistent operation, extends device lifespan, and contributes to overall system efficiency and user experience.

3.2.6.1 Lithium Ion Polymer Battery - 3.7v 100mAh - Adafruit

This battery is small enough that we could implement it into our device. Some special considerations when it comes to this battery are that we need to use boost converters to be able to power the MCU if the MCU requires a voltage above 3.7V to power, since putting two batteries in series would add to the size of the project. We would also need protection circuitry to prevent overcharging, over-discharging, and overcurrent.

3.2.6.2 CR2032 3V Coin Cell Battery by Duracell

CR2032 batteries typically come with a capacity of 225 milliamp hours, which means it can provide a current of 225 millamps for one hour. Our device most likely will not require a current that high, so the battery will last longer than an hour. These batteries are typically used to power wearables, like Apple AirTags and watches. Something to consider while using these batteries is they require special holders to be used. This can be a separate enclosure or surface mounted on the PCB.

3.2.6.3 Choosing a Battery

After considering our battery options, we have decided to choose the CR2032 battery. This battery has a higher capacity than the other two options in a small form factor. It also does not require special protection circuitry to prevent it from exploding, which is a big concern, given the nature of the project. The downside to choosing this battery is it is not rechargeable, which means we have to make the battery accessible to the user when designing the product.

	Attributes			
Battery	Size	Capacity	Voltage	Special Considerations
Lithium Ion Polymer Battery (100 mAh)	11.5 x 31 x 3.8 mm	100 mAh	3.7V	Protection circuitry required to prevent overcharging, over-discharging, and overcurrent
CR2032 3V Coin Cell Battery by Duracell	Ø 20 mm x 3.2 mm	225 mAh	3V	Requires a special holder to be used, which can be surface mounted to the PCB
Lithium Ion Polymer Battery (150 mAh)	19.75 x 26.02 x 3.8 mm	150 mAh	3.7V	Protection circuitry required to prevent overcharging, over-discharging, and overcurrent

Table 3.2.4.4 Battery Comparison

Again, due to the inherent design changes implemented throughout this project, a 9V battery was selected to replace the CR2032 to meet the load demand of 150 mA.

3.2.7 PCB Manufacturer

A PCB manufacturer that meets the goals of this project must be identified to produce a desirable and reliable result. As the development phase of this project is expected to go through multiple corrections, changes, and iterations during prototyping, selecting a manufacturer that values rapid turnaround time, reliable production, and affordability remains of the utmost importance during the selection process.

Although there are thousands of PCB manufacturers globally, a few of the most well-known manufacturers will be assessed as candidates for selection.

3.2.7.1 JLCPCB

The most popular manufacturer known for their affordability is JLC PCB. They provide high-quality printed circuit boards at low prices, and are especially used for anything between prototyping to small and medium scale production runs. JLC PCB offers a multitude of PCB configurations including multi-layer PCBs and flexible PCBs along with your traditional rigid PCB. However, they do not support rigid-flex PCBs. Additionally, they are well regarded for having fast manufacturing and delivering times, generally offering a 24-hour production time for most orders. Their site is user-friendly, allowing users to easily upload Gerber files for placing orders [\[41\]](#).

3.2.7.2 PCBWay

Another leading PCB manufacturer is PCBWay, who provides fabrication services ranging from prototyping to mass production or custom solutions. Similar to JLCPCB, they offer traditional boards, two layer boards, multi-layer boards, and flexible boards. However, they also fabricate rigid-flex boards and provide assembly services, along with component sourcing. PCBWay's site is equally as user-friendly as JLC PCB's, allowing users to upload Gerber files for quotes and ordering, with fast production times. Although they offer competitive pricing, fabrication is more expensive compared to JLC PCB, especially for flex PCBs [\[42\]](#).

3.2.7.3 Advanced PCB

Advanced PCB, formerly known as Advanced Circuits, 4PCB, APCT, and SDPCB, is the most well known PCB manufacturer in North America. They provide both basic and advanced circuit board services including prototyping, small to medium level production runs, and complex PCB designs. Advanced PCB is specifically known for their circuitry reliability, as they provide services for aerospace, defense, medical, and telecommunication industries, manufacturing standard PCBs, HDI PCBs, multi-layer PCBs, and rigid-flex PCBs with quick production times. Because of this, the cost to manufacture a PCB is drastically more expensive, as customers are paying for the reliability of highly advanced circuits [\[43\]](#).

3.2.7.4 Manufacturer Selection

Each of these manufacturers offer prototyping services for the PCB design complexity expected for this project. Thus, selection of the manufacturer should balance both reliability and cost to produce the desired result within the allocated budget. Although Advanced PCB provides extremely reliable PCBs, the cost for basic prototyping lies outside a reasonable budget for this project, especially considering our design is not expected to be highly complex. JLCPCB and PCBWay offer relatively similar results in regards to services and production speed. However, JLC PCB is marginally more economical for the needs of the project, and thus, will be selected as the manufacturer for our prototype.

3.2.8 Voltage Regulator

To power the device, we will be using a coin battery, which supplies 3V and only drops as the battery discharges. If we are using an MCU that takes 5V as an input, to regulate the output voltage, we need a boost converter to step-up the voltage. If we were to use an MCU that takes 1.8V as an input, we would need a buck converter or LDO regulator to step-down the voltage.

3.2.8.1 TPS61023 Boost Converter

The TPS61023 boost converter takes a minimum input voltage of 2V and outputs steady 5V supply at 1A. This is useful if we use an MCU or sensor that requires a 5V power supply. The chip, made by TI, is very thermally efficient, which is a good thing to take into consideration.

3.2.8.2 MCP1700 LDO Regulator

The MCP1700 LDO linear voltage regulator has a small drop out voltage and low current consumption, making it ideal for battery powered devices. It comes in many options when it comes to output voltage, including an option to output 1.8V. It also has some safety features, like over-current and over-temperature protection [\[44\]](#).

3.2.8.3 TPS 783 LDO Regulator

The next LDO regulator option is the TPS 783 linear regulator from Texas Instruments. Just like the previous LDO regulator, this would be used if we chose an MCU or if a sensor required a steady voltage below 3V. It also has a very low current consumption and drop out voltage [\[45\]](#).

3.2.8.4 Comidox Boost Converter

The next boost converter we will examine is a boost converter that is sold on Amazon that outputs 5V at 480 mA. It comes in a tiny package that measures at 11 x 10.5 x 7.5 mm. This would be useful because we are trying to minimize size with our device.

3.2.8.5 LTC1682-3.3

The final boost converter we will examine is the LTC1682-3.3 by Linear Technologies. It provides an output of 3.3V at 50 mA, making it perfect for MCUs and peripherals that use 3.3V to operate. It has a switching frequency of 550 kHz, making it ideal as we are staying under 1 MHz.

This boost converter also only uses capacitors to operate, rather than a mix of capacitors and inductors, making it simpler to implement into our device. It also comes in an SOIC-8 package size, which would help keep the device as small as possible.

3.2.8.6 Picking a Voltage Regulator

After comparing all 4 voltage regulators, since we chose an MCU that operates at 3.3V, we will be choosing the LTC1682-3.3 boost regulator. Some other advantages of choosing this boost regulator is it does not require inductors to operate and it has a low switching frequency. If we use an MCU that takes 1.8-3.6V, we will use the TPS783 as it has a smaller dropout voltage and has a smaller quiescent current. Table 3.2.6.5 provide a comparison that dictated component selection

	LDO			Boost		
Voltage Regulator	MCP1700	TPS 783	NCP 1117	TPS6102 3	Comidox Boost Converter	LTC1682 -3.3
Voltage Output	1.8, 2.5, 3.0, 3.3, 5.0V options	1.8, 1.9, 2.6, 3, 4.2V options	1.5, 1.8, 1.9, 2.0, 2.5, 2.85, 3.3, 5.0, and 12 V options	5V at 1 amp	5V at 480 mA	3.3V at 50 mA
Quiescent Current	1.6 microamps	0.5 microamps	6 mA	N/A	N/A	N/A
Dropout Voltage	178 mV at full load	175 mV at full load	1 V	N/A	N/A	75-120 mV
Size	4.62 x 4.71 x 3.62 mm	8.12 mm ² 2.9 x 2.8	6.5 mm x 7 mm x 1.8 mm	17.8 x 11.3 x 5.6 mm	11 x 10.5 x 7.5 mm	5.01 x 6.18 x 1.44 mm

Table 3.2.6.5 Voltage Regulator Comparison

Implementing the design changes of hardware V2 and hardware V3 as described in Chapter 6 found that the TPS 783 was unable to deliver the current demand of 150 mA, with full system integration and bluetooth connection. Because of this, the voltage regulator was changed to the NCP 1117, with fixed 3.3 V output.

This voltage regulator was selected because it is the recommended voltage regulator for the ESP32-WROOM, and is fully integrated with it on the corresponding ESP32 dev kit, making it more readily available to meet the time constraints related to this design.

CHAPTER 4 - STANDARDS & CONSTRAINTS

4.1 Industrial Standards

Understanding industrial standards is essential for engineers and designers to ensure that products are safe, reliable, and compatible with existing systems and technologies. These standards, developed by recognized organizations such as ISO, IEEE, and ANSI, provide established guidelines for design, manufacturing, testing, and quality assurance across various industries. Adhering to these standards not only promotes interoperability and compliance with regulatory requirements but also reduces development time, improves product performance, and enhances consumer trust. In a global market where consistency and safety are paramount, a solid grasp of relevant industrial standards is key to delivering successful and sustainable engineering solutions.

4.1.1 PCB Design Standards

PCB design standards play a critical role in ensuring the functionality, reliability, and manufacturability of electronic circuits across various applications. Developed by organizations such as IPC, IEEE, and ISO, these standards provide structured guidelines for layout practices, material selection, trace routing, spacing, via placement, and thermal management. Adhering to PCB design standards helps engineers avoid common pitfalls like signal interference, component failure, or manufacturing defects, especially in high-speed or high-density designs. These standards also promote consistency across design teams and streamline communication with manufacturers, reducing the risk of costly revisions or production delays. Understanding and applying PCB design standards is essential for producing high-quality, compliant, and efficient electronic systems.

4.1.1.1 General Design Considerations

Researching design considerations for PCBs is a crucial role as it will directly impact functionality, reliability, and manufacturability. Proper planning will allow for a successful and reliable product that optimizes usability and integration. Factors such as component placement, trace routing, layer stacking, and material selection of PCBs must be thoroughly researched and carefully evaluated to accommodate the specific requirements of the product while also enhancing electrical integrity and efficient power distribution. Addressing these needs early will prevent unnecessary and costly challenges and revisions later in the prototyping and testing process.

For the purposes of this product, the PCB design should keep the overall physical and electrical specifications in mind. The PCB must be able to accommodate the MCU, sensor, transmitter, and power supply while being sufficiently compact enough to either fit reasonably with or within most standard feminine hygiene products or fit within an external attachment connected to the sensors. Since most products are form fitting, the PCB must be capable of flexing, twisting, and moving with such products as to be

virtually indistinguishable by the user from the product itself. Additionally, the PCB may be subject to adverse environmental conditions including but not limited to heat, fluid contact, and foreign particles and is expected to be reused continuously. Thus, the PCB design should maximize flexion, movement, compactibility, and durability while simultaneously meeting fundamental electrical requirements and cost efficiency.

IPC-2221 provides guidelines and recommendations for the design of PCBs, specifying parameters to create a robust and reliable electronics system. These parameters include trace width, spacing, and layers to help maintain signal integrity, power distribution, and thermal management. Additionally, the standards provide guidance to design PCBs with design for manufacturability (DFM) in consideration, with recommendations for efficient fabrication, assembly, and testing to help minimize issues during the manufacturing process and increasing efficiency and output during production. Finally, IPC-2221 standards help ensure quality and reliability when designing PCBs, with criteria for quality control and testing to verify completed PCBs meet industry standards.

4.1.1.1 Board Constraints

In order to meet these specifications, a bare board size and shape must be established. Two potential options exist for how the PCB may integrate with the feminine hygiene product. The PCB may be directly integrated within the product, and thus the board size and shape must mirror that of the hygiene products it is expected to be compatible with. The second option involves the sensor to be separate and wired to the PCB rather than mounted. This would mean that only the sensor sits within the hygiene product and that the PCB sits externally on a waistband or belt.

For a directly integrated PCB, the PCB size must be less than or equal to that of the product. Typical pads have three main sizes: regular, large, and extra large. Regular sized pads accommodate normal flow with a typical length of 180 to 220 mm and width of 60 to 100 mm excluding wings and absorbency of 15-20 mL. Large pads accommodate moderate flow with a length of 220 to 260 mm, width of 60 to 100 mm, and absorbency of 20-30 mL. Extra large pads accommodate heavy flow with a length of 260 to 300 mm, width of 60 to 100 mm, and absorbency of 30-40 mL. For the PCB to be compatible with all three sizes, the board must be within 180 mm in length and 60 mm in width [\[46\]](#).

An externally mounted PCB is likely to be integrated along with the waistband and thus must still be compact and flexible to be virtually undetectable. Mounted components should be arranged in a linear pattern to maximize waistband compatibility. PCB width should be 2.5 to 5 cm. Length has no constraint but should be effectively minimized.

4.1.1.2 Materials and Components

The materials composing the PCB should be selected to not hinder electrical performance. As our PCB is expected to be a simple design, a board with a standard FR-4 substrate, copper layer, solder mask, and silkscreen is likely to be sufficient to meet the electrical design. However, adverse environmental conditions require consideration of

additional protection to minimize unnecessary damage, corrosion, failure, or performance degradation to either the board or its components. IPC-2221 provides recommendations depending on the required dielectric properties, thermal conductivity, and mechanical strength of the application.

Several methods exist for environmental protection. Conformal coating is a method that applies a thin protective layer on the surface of the PCB that blocks temperature fluctuations, chemicals, dust, and moisture. Common conformal coating materials include acrylics, silicone, urethane, and epoxy which are generally applied via spray coating, dip coating, or brush coating to cover solder connections, components, and traces.

Encapsulation is another protection method that involves covering the PCB or specific components with a protective layer. This protective layer is either poured or injected onto the PCB, increasing mechanical strength, electrical insulation, and resistance to shock and vibration.

This method provides the PCB with protection from physical damage, chemicals, moisture, and dust. Varnish/Dipping provides protection against moisture, corrosion, and some degree of mechanical stress. This method is applied by dipping or coating the PCB with a varnish to create a protective layer. This form of protection is generally a more cost-efficient method. Finally, environmental housing units can be specifically designed and developed for the PCB. providing protection against pollutants such as water and dust. This can also provide seals around ports, connectors, and other openings to minimize pollutants from entering [\[47\]](#).

4.1.1.3 Component Placement Order

Minimizing issues regarding electrical performance can be mitigated with proper placement of components on the PCB. Generally, good practice is to first place connectors, then power circuits, then precision circuits, then critical circuits and place any remaining components last. However, component susceptibility to noise, routing, and power levels can alter the placement priority. Electrical design considerations will be further discussed in a later section as recommended by IPC-2221 [\[48\]](#).

4.1.1.4 Orientation, Placement, and Organization

Planning of PCB orientation, placement, and organization can help increase efficiency, minimize cost, and reduce the number of assembly steps required. Similar components should be similarly oriented to make soldering more efficient and prevent unnecessary mistakes from occurring.

Additionally, parts should not be placed on the solder side of the PCB that is expected to be behind plated through-hole parts. Finally, it is generally good practice to place surface mount components on one side of the PCB while placing all through hole components on the top side.

4.1.1.2 Electrical Design Considerations

Just as the physical design considerations must be planned to maximize performance of the PCB, electrical design principles must be considered to mitigate any electrical performance issues. The design must keep in mind the route of power, ground and signal traces, and signal reliability in order for the PCB components to work as desired.

4.1.1.2.1 Power and Ground Planes

A key rule in PCB layout design is to keep the power and ground planes within the internal layers of the board. Maintaining them in a central location and placed symmetrically can mitigate the possibility of bowing or twisting. Which can displace components and cause damage to the board. Additionally, common rails for each supply should be used to maintain robustness of traces and mitigate daisy-chaining components together which can create electrical fires and overloaded circuits from the series resistance.

Placement of the power and ground planes can further reduce high-voltage signal interference with low-voltage or current control circuits. The grounds of each power stage should be separated if possible. If this is not possible, they should be placed near the end of the supply path. If the ground place is placed in the direct center, a small impedance path should be added to help minimize interference. Finally, digital and analog grounds should be similarly isolated. Analog signals should cross the analog ground plane as few times as possible to minimize capacitive coupling.

4.1.1.2.2 Track Design

Track designs connect signal traces across a design. IPC-2221 provides specifications to help maintain impedance control and signal integrity. Traces should always be as short and direct as possible, either horizontally or vertically. Turns should generally be 45 degrees. While 90 degree turns are possible, sharp right angle bends generally impact signal integrity and should be discouraged. For dual-sided PCBs, traces should try to maintain a perpendicular relationship, meaning if traces are horizontally routed on one side, the other side should be vertically routed.

Trace width will be dictated by the current that it is expected to carry. Thin tracks are limited by how much current they can take. Tracks that are 10 mils in thickness can only carry approximately 1 A while a 250 mils track can carry 15 A with a 30 degree Celsius rise in temperature. Trace width calculators exist to help with PCB design and multiple nets are likely to be needed for different currents throughout the circuit.

4.1.1.2.3 Pad and Hole Dimensions

Determining pad and hole dimensions and ratios is important to consider early in the design process. The smaller the pads and holes gets, the more critical it is to determine the correct pad to hole ratio, especially when working with via holes. Additionally, the

shapes of the PCB pads would be considered as footprints can vary with the assembly and manufacturing process. Wave soldering requires a larger footprint compared to infra-red reflow soldering.

4.1.1.2.4 Signal Integrity and Interference

Ensuring circuit performance necessitates signal integrity is maintained throughout the PCB while radio-frequency and electromagnetic interference is mitigated. Proper trace routing often avoids these issues. When designing the PCB layout, parallel tracks should be avoided as tracks running parallel typically have more crosstalk. If traces must cross, they should be crossed perpendicularly to reduce capacitance, mutual inductance, and crosstalk.

Additionally, selection of components can help maintain signal integrity. Semiconductors that generate low electromagnetic radiation should be used while antennas should be eliminated as they can radiate electromagnetic energy and large loops of signal and ground-return lines carrying high frequencies. When designing a radio frequency PCB, a ground grid placed over the PCB can help keep the return lines reasonably close to the signal lines. Multilayer boards can achieve this with a ground plane.

4.1.1.2.5 Thermal Considerations

Lastly, thermal considerations must be made to maintain performance and mitigate damage. Large, complex boards and designs with high component densities and fast processing speeds are generally more prone to heat-related challenges. However, smaller boards should still be carefully designed for proper heat management and dissipation.

Components that generate significant amounts of heat should be identified using their respective datasheets and reading the thermal resistance ratings. Guidelines for re-directing heat away from these components should then be taken per IPC-221 which provides recommendations for heat dissipation, thermal vias, and component placement for those generating heat.

Placement of components generating a significant amount of heat should be considered as the more heat a component produces, the more space it will require to facilitate cooling and dissipation of heat. Sensitive and critical components should also be placed away from heat generating components. Optimizing thermal management involves maintaining a uniform operating temperature across the entire PCB, using thermally conductive planes to dissipate the heat over a larger area. This will help improve heat transfer and expedite the cooling process.

If thermal issues still persist, cooling methods such as cooling fans, heat sinks, and thermal reliefs need to be considered, especially for wave soldering on multiplayer PCBs and PCBs containing a lot of copper. Heat sink paste can be used to artificially create heat sinks. If through hole components are used, thermal reliefs should be considered to slow down heat transfer through the leads, especially when a via or hole connects to a ground

or power plane. Teardrops can further be added to the junctions of traces and pads as an extra buffer in thermal management.

4.1.1.3 Special Considerations for Flex and Rigid Flex PCBs

IPC Standards contain a plethora of sub-standards for each aspect of designing including solerability, packaging, cable and wire harness, assembly, electronic enclosures, components, and surface finish specifications among many others. IPC-2222 and IPC-2223 provide specific standards for Rigid and Flex PCBs respectively. Due to the nature of both flexible and rigid-flexible PCBs, special design considerations must be made for high-yield and board durability. These considerations must be balanced with the needs and requirements of component placement and trace routing to maintain circuit functionality. Additionally, determining whether the flex PCB is expected to have a static or dynamic bend can help determine PCB design. Static bend designs, in which circuit sections are folded during assembly and then left in the fixed position, provide significantly more freedom for layer count and the type of copper used within the PCB. Dynamic bend designs that are expected to move, bend, twist, or roll continuously should minimize the number of layers and utilize adhesiveless substrates. Minimum allowable bending radius should be calculated using the following equation from IPC-2223 [49]:

$$R = \frac{C(100-E)}{2E} - D$$

R = Minimum Bend Radius

C = Copper Thickness

D = Dielectric Thickness

E = Allowed Copper Deformation (%)

Equation 4.1.1.2 Minimum Bend Radius for Flex PCB

The application of the PCB will dictate the allowed copper deformation since copper is susceptible to fatigue and fracture from flexion. 16% is allowed for a single-crease installation of RA copper, 10% for “flex to install” and 0.3% for dynamic flex designs. Minimum bend radius should remain smaller than the intended bend radius to prevent fatigue from occurring at the edges of the board. This helps extend the life span of the PCB.

Copper tracing must be carefully done to minimize damage due to flexion. Traces should be kept perpendicular to the expected flex-circuit bend. In scenarios when this is not possible, traces should curve as gently as possible using arc rather than hard 45 degree turns. Traces should also gradually taper down from the pads, as sudden width changes can create weak spots susceptible to fatigue.

Exposed copper pads for surface mounted components require extra support and the copper is likely to detach from the polyamide substrate from repeated flexion. Through hole plating has an inherently built in mechanical support for the exposed copper and is thus preferable for flex PCBs. Additionally, vias need to be minimized as they too are

susceptible to fatigue. The copper annulus of the via must be kept at least 20 mils from the rigid to flex board interface [50].

4.1.1.4 JLC PCB Manufacturing Capabilities and Requirements

Along with the universal design expectations standardized in IPC standards, PCBs must also meet manufacturability criteria designated by individual manufacturers. These criteria layout specific dimensions, layers, clearances, and structures that a design must adhere to in order for it to be fabricated by the manufacturer. The selected manufacturer for PCB prototyping is JLC PCB whose industrial and manufacturing standards for flex PCBs are provided below:

4.1.1.4.1 Layer Count

JLC PCB is limited to 1 or 2 copper layers within the FPC. Rigid-Flex PCBs are NOT supported.

4.1.1.4.2 Flexible Printed Circuit (FPC) Stack-Up

PCBs can either be single-sided or double-sided. For a single-sided PCB, the copper and overlay is placed on the same side with the inner PI stiffener thickness being 25 μm .



Figure 4.1.1.3.2.1 Single-Sided FPC (reprinted with permission from JLC PCB)

A double-sided PCB will have copper on both sides, with the same stiffener thickness (25 μm).

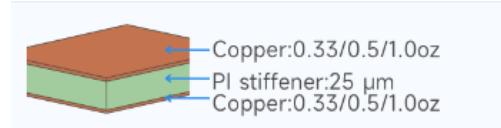


Figure 4.1.1.3.2.2 Double-Sided FPC (reprinted with permission from JLC PCB)

4.1.1.4.3 Dimensions

The absolute maximum dimension limit is 250 x 500 mm is allowed which includes the required handling edges. Excluding the handling edges, PCB design must be within 234 x 490 mm. No minimum dimension limits exist. However, circuits smaller than 20 x 20 mm are recommended to be panelised.

The thickness of the completed circuit without the stiffeners is 0.07 or 0.11 mm for a single sided PCB and 0.11, 0.12, or 0.2 mm for a double-sided PCB. Copper thickness can be 18 μm (0.5 oz) or 35 μm (1 oz) for a single sided PCB and 12 μm (0.33 oz), 18 μm (0.5 oz), or 35 μm (1 oz) double-sided. A tolerance of ± 0.05 mm is allowed.

Laser Direct Image (LDI) is used for the dry film process, providing a higher degree of accuracy compared to LED exposure. LDI machines further support automatic alignment to eliminate pad offset issues. A ENIG surface finish is applied, depositing a nickel-gold coating to prevent oxidation of exposed pads.

4.1.1.4.4 Holes

Hole diameters can be 0.15 - 6.5 mm with a tolerance of ± 0.08 mm. Plated through holes are recommended to have a maximum diameter of 5 mm to minimize production risk. Plated slots are required to be 0.50 mm in width or wider. Non-plated slots have no minimum constraints although there must be at least 0.2 mm of copper clearance around them.

Castellated holes (partially plated half-holes that sit on the edge for press-soldered connectors) must have a hole diameter ≥ 0.3 mm. Distance between hole and board edge must be ≥ 0.5 mm and hole to hole distance must be ≥ 0.4 mm.

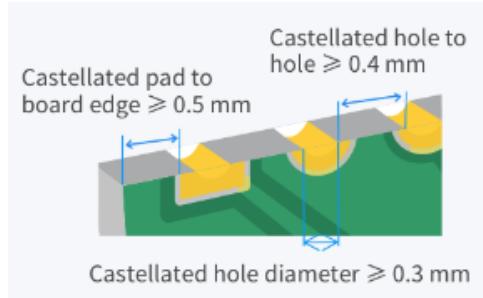


Figure 4.1.1.3.4.1 Hole Tolerances (reprinted with permission from JLC PCB)

Via hole size must be ≥ 0.15 mm and via diameter must be ≥ 0.35 mm. JLC PCB recommends a via hole size of 0.3 mm and a via diameter of 0.55 mm.

4.1.1.4.5 Traces

JLC PCB provides the following minimum trace width / spacing constraints:

1. 12 μm (0.33 oz) copper: 3/3 mil with an absolute limit of 2.2 mil which should be avoided.
2. 18 μm (0.5 oz) copper: 3.5/3.5 mil
3. 35 μm (1 oz) copper: 4/4 mil

Trace width tolerance is $\pm 20\%$. Pad to trace clearances are provided below:

1. Distance between via ring and trace must be ≥ 0.1 mm
2. Distance between exposed pad to trace must be ≥ 0.15 mm

Ball Grid Array (BGA) Constraints are specified as:

1. Pad Diameter must be ≥ 0.25 mm
2. Pad to trace clearance must be ≥ 0.2 mm

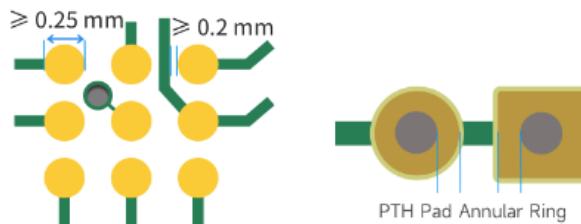


Figure 4.1.1.4.5.1 Trace & Pad Tolerances (reprinted with permission from JLC PCB)

Furthermore, the annular ring for a plated through hole must be ≥ 0.25 mm with an absolute limit of 0.18 mm. Non-plated through hole to copper clearance must be ≥ 0.2 mm.

4.1.1.4.6 Overlay / Solder Mask

Coverlay is offered in either yellow, black, or white (yellow is recommended). Coverlay expansion of one side is 0.1 mm and the distance between a trace and the coverlay opening must be ≥ 0.15 mm.

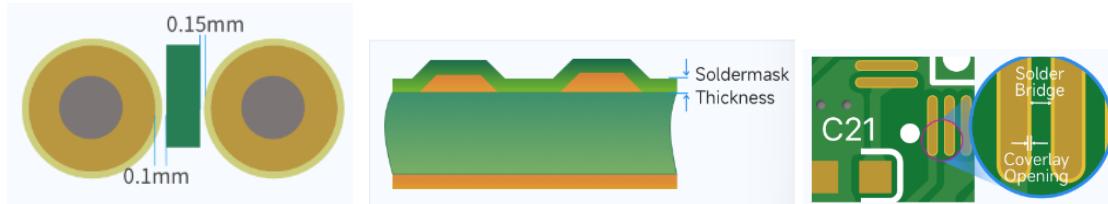


Figure 4.1.1.4.6.1 Solder Mask Tolerances (reprinted with permission from JLC PCB)

Coverlay thickness constraints are specified as:

1. PI: 12.5 μm , glue: 15 μm (on 12/18 μm copper)
2. PI: 25 μm , glue: 25 μm (on 35 μm copper)

Solder bridge width must be at least 0.5 mm. JLC PCB recommends keeping overlays over vias.

4.1.1.4.7 Silkscreen

1. Character Height must be ≥ 1 mm
2. Character Line Width must be ≥ 0.15 mm
3. Character to Pad Clearance must be ≥ 0.15 mm

4.1.1.4.8 FPC Outline

Laser Outline

1. Copper to board edge must be ≥ 0.3 mm

2. Copper to slots must be \geq 0.3 mm
3. Outline Tolerance is \pm 0.1 mm or \pm 0.05 mm upon request

Gold Finger Pad to board edge clearance must be 0.2 mm. Otherwise, gold fingers will be cut back. Castellated pads are exempt from this constraint.

4.1.1.4.9 Stiffeners

JLC PCB provides the following stiffeners in various options:

1. PI Stiffeners
 - a. Thickness Options: 0.1, 0.15, 0.20, 0.225, or 0.25 mm
2. FR4 Stiffeners
 - a. Thickness Options: 0.1 or 0.2 mm
3. Stainless Steel Stiffener:
 - a. 0.1, 0.2, or 0.3 mm

JLC PCB also provides 3M Tape options, either 3M9077 (0.05 mm thick, heat-resistant) or 3M468 (0.13 mm thick, non heat-resistant). They also provide EM 18 μm thick, black shielding film.

4.1.1.4.10 Manufacturer Specific Design Considerations

Finally, JLC PCB provides additional Flex PCB design considerations and parameters. Impedance calculations should account for a core polyimide ϵ_r of 3.3, a overlay ϵ_r of 2.9, and a core polyamide thickness of 25 μm .

When designing, JLC PCB recommends using EasyEDA, as it integrates the stiffener layer within the design. Other miscellaneous design constraints should match those expected from rigid PCBs in regard to holes, traces, soldermask, and silkscreen [51].

4.1.2 Communication Protocols

Communication protocol standards are essential in ensuring reliable, consistent, and interoperable data exchange between electronic devices and systems. These standards define the rules, formats, and timing for data transmission, enabling seamless communication across different hardware and software platforms. Developed by organizations such as IEEE, ISO, and IETF, communication protocols like UART, SPI, I²C, USB, TCP/IP, and CAN are widely used in applications ranging from embedded systems to large-scale networks.

Adhering to these standards ensures compatibility, reduces integration complexity, and enhances system scalability and maintainability. Understanding communication protocol standards is crucial for engineers to design systems that are robust, efficient, and capable of interacting within broader technological ecosystems.

4.1.2.1 Bluetooth Classic

Developed in 1994 by Dr. Jaarp Haartsen out of a need for a way to connect devices wirelessly, Bluetooth Classic is the protocol that we use for applications where data needs to be continuously streamed, such as audio streaming for things like wireless headphones and speakers. It streams data over 79 channels in the 2.4 GHz unlicensed industrial, scientific, and medical (ISM) frequency band. Bluetooth Classic's Enhanced Data Rate allows for faster data transfer at 3Mb/s compared to Bluetooth Low Energy's maximum data transfer rate at 2 Mb/s [\[52\]](#).

4.1.2.2 Bluetooth Low Energy

The communication protocol that we used for our project is Bluetooth Low Energy, as we did not need to continuously transfer data between devices. Unlike Bluetooth Classic, which is designed for continuous, high-throughput data transfer, BLE is optimized for applications where periodic data transfer is sufficient, such as in IoT devices, wearable technologies, and sensor networks. Bluetooth Low Energy uses 40 channels in the 2.4 GHz ISM band, compared to the 79 channels in the ISM band that Bluetooth Classic uses. Bluetooth Low Energy achieves its low power consumption by operating in short bursts, allowing devices to spend most of their time in sleep mode. In contrast, Bluetooth Classic maintains a continuous connection, which results in higher energy usage. By only waking the device for brief communication, BLE drastically extends battery life, which is a critical factor for battery-powered devices like ours. Another feature of Bluetooth Low Energy that Bluetooth Classic does not support is connectionless modes [\[53\]](#), [\[54\]](#).

4.1.2.3 UART

Universal Asynchronous Receiver/Transmitter is a serial communication protocol used to transfer information between devices. It is one of the simplest serial communication protocols as it only requires two wires to transfer data and it is asynchronous, meaning the two devices do not need a clock. Without using a clock, both devices need to send and read information using the same frequency, known as the baud rate.

UART can be configured as simplex, half-duplex, or full-duplex. Simplex means the data can only be sent in one direction. Half-duplex means data can be sent in both directions but only sent in one direction at a time and full-duplex means data can be sent in both directions at any time. The drawback to using UART is it can only communicate between two devices, meaning multiple masters or slaves are not achievable using UART.

Data is organized into packets to be sent between devices. Packets start with a start bit that tells the receiving device to start reading data. After the start bit, the actual data is sent, which usually takes up between 5 to 9 data bits. The data can be followed by a parity bit, which is used for error detection. The packet is concluded with 1 or 2 stop bits to tell the receiver that the packet is finished sending [\[55\]](#).

Protocol Layer	Function
Physical Layer	Defines the specifications for the hardware used for transferring data.
Link Layer	Configures the LE radio to form communication links.
Host Controller Interface Layer	Interface between the upper-level protocols and lower-level protocols.
Logical Link Control & Adaptation Protocol Layer	Serves as a liaison between the upper layers and lower layers
Security Manager	Responsible for pairing and authenticating devices and encrypting data sent between them.
Attribute Protocol	Bluetooth Low Energy Devices store data using a data type called an attribute and this layer defines the structure of an attribute.
Generic Attribute Profile	This layer provides a hierarchy for storing data.
Generic Access Profile	Defines procedures for how devices can communicate with others through broadcasting or connecting.

Table 4.1.2.2.1 BLE Protocol Layers

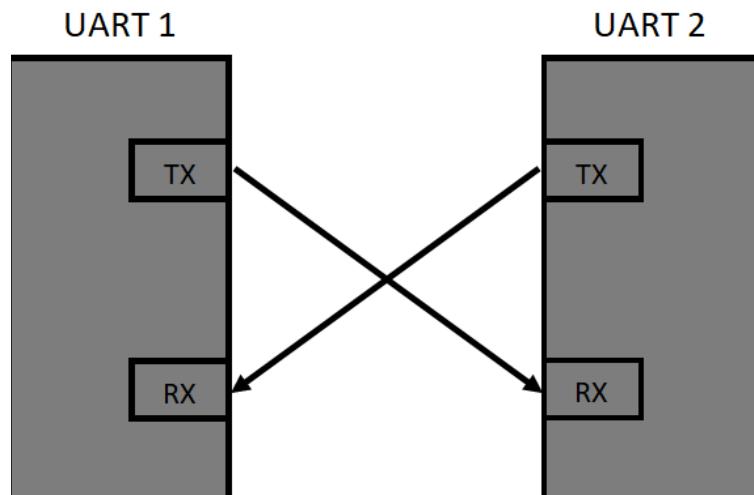


Figure 4.1.2.3.1 UART Configuration (created by Authors)

1 START BIT	5 TO 9 DATA BITS	0 TO 1 PARITY BITS	1 TO 2 STOP BITS
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Figure 4.1.2.3.2 UART Bit Stream Layout (created by Authors)

4.1.2.4 I2C

Inter-Integrated Circuit (I2C) is a synchronous serial communication protocol. Unlike UART, I2C can only be configured as a half-duplex system, meaning data can be sent in both directions but only one way at any time. It can also be used to communicate between multiple devices, through multiple masters or multiple slaves. I2C uses two wires to operate: Serial Clock (SCL) and Serial Data (SDA).

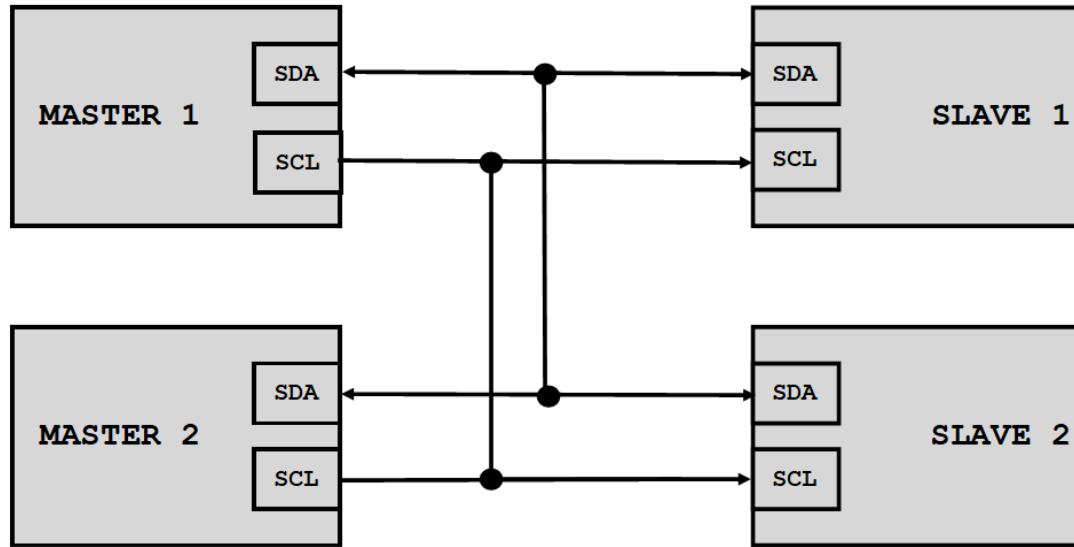


Figure 4.1.2.4.1 I2C Configuration (created by Authors)

Instead of packets, data is sent in messages. Each message has a start condition, which means data starts sending when SDA is changed from low to high or high to low, depending on the condition. Once the start condition has been sent, the address of the slave is sent. After acknowledgements have been sent, data is sent and acknowledged and the stop condition is sent to stop the flow of information.

START	ADDRESS 7-10 BITS	READ/ WRITE BIT	ACK/ NACK	DATA 8 BITS	ACK/ NACK	DATA 8 BITS	ACK/ NACK	STOP
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Figure 4.1.2.4.2 I2C Bit Stream Layout (created by Authors)

When it comes to standards for I2C, there are different transfer speeds that can be used to transfer data. Each speed has a different use case, such as if you are using a real-time system or reading sensor data. These standards allow I2C to adapt to various applications, from low-speed, low-power devices to faster communication needs [56], [57].

Name	Bus Speed
Standard-mode (Sm)	100 kbit/s
Fast-mode (Fm)	400 kbit/s
Fast-mode+ (Fm+)	1 Mbit/s
High-speed mode (Hs-mode)	3.4 Mbit/s
Ultra Fast-mode (UFm)	5 Mbit/s

Table 4.1.2.4.3 I2C Modes

4.1.2.5 SPI

Serial Peripheral Interface (SPI) is another synchronous serial communication protocol that we can use to communicate between the Bluetooth Low Energy module and the MCU. This system is a full-duplex system, meaning data can be sent both ways at any time. It uses 3 wires plus a wire for every slave device used in the system. The 3 wires that are always used are: Master Output/Slave Input (MOSI), Master Input/Slave Output (MISO), and Clock (SCLK). Then each wire added for each slave device is used to select which 2 devices are transferring data.

If the master is limited in wires, the chip select can be daisy chained between slaves, meaning there would only be 4 wires used in the system. Data transfer is always initiated by the master, as it is the one with the clock source. The master first chooses which slave it wants to send information to using the chip select lines. It can then transfer data to the slave through the MOSI line and the slave can send information back through the MISO line [58].

4.1.3 Development Environment Standards

The development environment has several standards that must be met to ensure the project runs smoothly, efficiently, and adheres to a certain level of professionalism. These standards cover the integrated development environments (IDEs), coding practices, version control, and software and hardware compatibility.

IDE: The project primarily used Visual Studio Code for app development and Arduino IDE for embedded development, which was optimized for Arduino hardware such as the

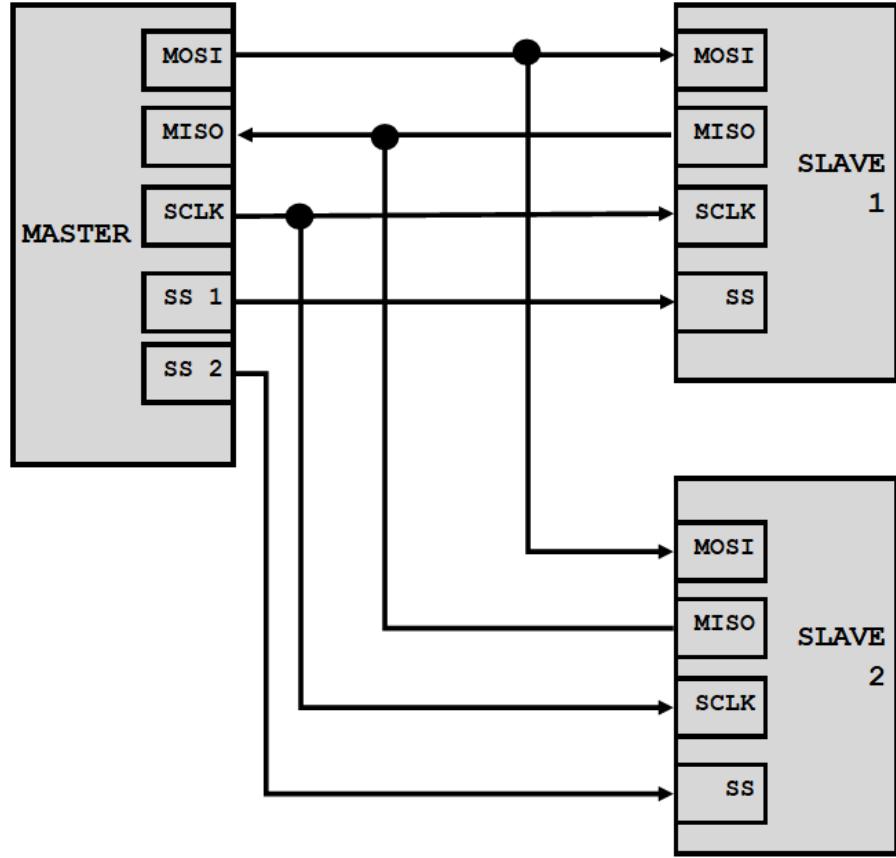


Figure 4.1.2.5.1 SPI Configuration (create by Authors)

ESP32. IDEs had to run and compile code correctly and efficiently so that faulty code was not accidentally shown to be correct, causing issues during our progress. The IDE had to adhere to a certain level of privacy control to allow the user to write sensitive code and information without it being publicly available. The IDE usage had to adhere to the ISO/IEC 11207, which is the international standard for software lifecycle processes, ensuring that all tools used in development are aligned with industry practices for software engineering and development.

Coding Practice: The project adhered to standard C and C++ coding practices, following that of MISRA C/C++ guidelines (Motor Industry Software Reliability Association), which is designed to ensure the safe, secure, and reliable development of software for embedded systems. Although it was not used, we ensured that any utilized object-oriented programming was implemented according to the ISO/IEC 14882 (the standard for C++), to ensure the best practices to maintain and reuse code.

Version Control: GitHub was able to be used for version control with adherence to the ISO/IEC 14764 for software configuration management, but due to limited sharing and need for version control, we used chat logs to post different files. However, using version control ensured that changes were systematically controlled, revisions were maintained,

and collaborative work (if any) was properly tracked. Additionally, branching strategies, pull requests, and issue tracking had followed the industry standard, which is the GitFlow workflow. This helped promote consistency in the team's development process.

Testing and Debugging: All code was tested using built in debugging tools available in the IDE, which offered advanced debugging capabilities such as real-time trace analysis and power consumption optimization. The testing process adhered to IEEE 829, which is the standard for software and system test documentation. This ensured that tests are properly documented and traced. Unit testing was not incorporated due to lack of complexity but it can be used and guided by the ISO/IEC 291119 (software testing standards), which ensures that individual models are validated before integration into the main system.

4.2 Real-World Constraints

Along with the applicable engineering constraints for our design, this project must also consider practical constraints in regards to its development and application. These constraints define the practical boundaries of which we must operate in order to meet the expectations set for our team. The real-world constraints that are specifically applicable to the development and execution of our project are specified as follows.

4.2.1 Timeline

The most important constraint to consider during the development of this project is its timeline expectation. A deliverable product must be presented at the end of Senior Design 2, creating a non-negotiable deadline and a nine month time frame for our team to brainstorm, plan, research, design, prototype, fabricate, develop, and troubleshoot as required, with no extensions or flexibility. This constraint limits what can feasibly be accomplished in this time frame. The success of our product is assessed based on meeting the performance metrics stated within this paper. Thus, greater priority will be placed in making decisions that allows us to efficiently deliver a product that meets these metrics prior to innovating the design and enhancing its capabilities to achieve the reach goals specified for our project.

To meet this expectation, our team must consider and anticipate uncontrollable challenges and obstacles that will hinder us from meeting the deadline. One such obstacle is the ordering of parts and components when constructing the prototype. Certain parts, such as the PCB, are susceptible to delays after ordering due to supply shortages or shipping delays that further restricts our team's ability to proceed and meet the designated timeline.

Another uncontrollable factor are the inherent issues that will arise when developing a new product. This project will require significant amounts of testing, debugging, troubleshooting, reworking, and redesigning. The problems and errors that will arise from this will vary in difficulty and time necessary to resolve them. Thus, the unpredictability of these setbacks must be considered as they can severely affect our team's ability to meet

the expected deadline, which will negatively impact our team's deliverable and performance assessment.

To mitigate this, our team must remain proactive during the duration of this project, effectively managing our time wisely, taking responsibility for the aspects each individual member is responsible for, remaining productive, collaborating and communicating effectively, and most importantly working as a team to achieve a common goal. Effectively remaining diligent in this way allows our team to effectively meet checkpoints and manage factors that we can control early in the process, giving us ample time to account for unforeseen setbacks and delays while still meeting the designated deadline.

4.2.2 Environmental and Physical Constraints

The application of this project presents unique environmental and physical constraints that must be considered in the final design. Our device is expected to operate within extremely close proximity to the human body, integrating itself with feminine hygiene menstrual products. Thus, development and testing of our device should simulate these environmental conditions to ensure device resiliency. Additionally, feminine hygiene products are used in constricted spaces which necessitates that our device reflect these same constraints in order to be integrated seamlessly with these products.

The most obvious physical constraint is overall size and compactibility. The overall size of the device must be minimized as much as possible to be virtually undetectable and indistinguishable from the hygiene product itself. This further necessitates the device to be capable of moving, flexing, and twisting with these products as well. Integrating a complete electronic device with peripherals and components that can achieve these physical dynamic demands presents significant challenges to meet these constraints.

The device must also account for environmental constraints. Use and application of our project may expose the electronic system to dust particles from hygiene products or clothing integration. Additionally, the close proximity to human skin further exposes it to the user's higher body temperature and bodily fluids.

Average human body temperature sits at 37°C which is a stark difference from room temperature at 20°C. This temperature can elevate if the device is placed underneath clothing or if the user goes outside for extended periods of time. If any components produce significant heat or if the overall circuit is susceptible to heat damage, the device could quickly fail under these conditions.

The nature of its application also exposes the electronic system to bodily fluids which must be accounted for. The sensors utilized within the device have a high probability of coming into contact with blood, sweat, or vaginal discharge as they detect the level of fullness of the feminine hygiene product being used. The PCB and device itself has a lower probability of coming into contact with such fluids but should still be made in such a way that if it were, the device remains functional and resilient. Providing protection

from such contaminants can be rather difficult as such fluids have varying chemical structures and pH levels, and sheer volume can be expected to vary within a wide range, depending on the user's flow. Additionally, variation in these fluids from user to user should also be considered as it is possible to differ significantly in various ranges.

Accounting for these environmental constraints and providing the necessary protection presents a unique challenge. Protection in the form of protective coating of the electronic device allows for the device to maintain physical attributes (such as dynamic flexing) while simultaneously maintaining compactness of the device. However, if protective coating is insufficient, a housing unit may have to be engineered which may limit and restrict the necessary physical constraint previously mentioned.

Although direct human testing is restricted for this project, significant testing will be done to verify these environmental requirements are met, in the form of synthetic blood and fluids, throughout the design process. This should allow us to provide a close simulation of the environment the device is expected to operate within, providing guidelines for future replication and innovation.

4.2.3 Economic

This project also has economic constraints associated with it that significantly impacts the decisions that will be made for its fabrication. As the sponsor, Gabriela Mercado, presented this project as a potential marketable business product that is expected to be utilized with everyday menstrual hygiene products, our design must be as cost effective as possible so that demand from everyday consumers (if placed in the market) can remain sufficiently high enough to be profitable. Thus, our team should consider the limitations of what everyday consumers would pay for the product we are attempting to develop and balancing this with the product's performance expectations.

Managing this constraint can be rather difficult as even selecting the most basic MCU, transmitter, sensor, and power supply significantly drives up the expected price of the end product reaching the limit of what a consumer may be willing to purchase. This consideration has not considered the price of the PCB, voltage regulation, housing unit, and other miscellaneous parts that are inherently necessary to create a functional design. Furthermore, the associated physical constraints for our project noted in the previous section exponentially raises the difficulty of meeting the economic constraint.

In order for the end product to be applicable in the real-world, our final design must be extremely compact and conform to various shapes, sizes, and movements as to be virtually undetectable and indistinguishable from standard feminine menstrual hygiene products. Additionally, it must be reasonably resilient to fluids and solids while also being physically resilient from dynamic stress, strain, torque, and compression. To develop a fully operational electronic system that can operate within these physical conditions drastically raises the price for the PCB and its peripherals that can make it nearly impossible to remain within a reasonable budget.

Fortunately, this budget constraint primarily applies to the end product and not its actual development. This provides us with a significant degree of freedom when prototyping and testing which could result in broken components or parts. However, our team is still responsible for the overall cost of the project, and thus it is within our best interest to minimize this as much as possible despite having virtually no budget constraint during development from our sponsor.

Our team thoroughly researched the various technologies that existed for the components that we expect to integrate within our design and selected them based off of the physical and electrical constraints of the project. The economic constraint then heavily dictated the part selection as we were required to choose the most cost effective parts that were cheaper and had greater limitations rather than parts that optimized performance and functionality for our project's goals. This allows us to create a final design that meets fundamental performance metrics at minimal cost to meet our projects associated economic constraint.

4.2.4 Sustainability and Reliability

Our project is ideally a sustainable and reliable product. We want something our users will be able to reuse multiple times not just because it reduces cost and hassle imposed on the user but because it's also sustainable and more environmentally friendly. Obviously with this in mind the limiting factors behind reusability are reliability concerns and design constraints.

Reusable electronics are not uncommon, it's only recently that many forms of disposable electronic devices have become popular. Our project has many problems that make reusability difficult. These problems mostly come from the fact that our project is a wearable hygienic electronic device, if users are to wear our device they will want and need to clean it which creates multiple roadblocks we need to overcome to make the product reusable.

Our device needs to be ingress protected to a higher degree than most devices and it needs to use peripherals that have a higher ingress protection. Our sensor is one to note in particular. If we choose to use a solid state sensor for our device this will expose contact pads that will need to be protected from corrosion and damage when cleaned or worn regularly. This is not entirely impossible, with modern anodizing techniques or careful cleaning practices we can achieve a level of protection that is safe for our sensor.

The choice for us is how to balance these methods. If we choose to use anodizing it becomes much more expensive to design and produce our device and if we instead have the user follow specific cleaning practices for our device we lose user-base and one of our most marketable aspects being convenience. The protections required for the rest of the device, PCB, transmitter, MCU, etc can be accomplished using standard ingress protection techniques.

Reliability constraints need to be kept in mind for more reasons than just reusability. While the reusability does affect our devices reliability it is also constrained in more ways. Our device is designed to be small, discrete, and comfortable to wear. Because of this size constraint we are very limited in which components we can use which can hurt our devices reliability. Simply the less choices we have the less options there are to choose reliable components. We have good options when it comes to MCU's and PCBs but there may be issues when looking for power supplies, voltage regulators, and sensor applications. When these components are limited by size their reliability often suffers which is a concern for our group because we want to have a product that can be reusable and reliable with consistently high accuracy.

I think it's important for our project to keep reliability in mind and try to create a device that is first reliable and second reusable. If our device cannot produce results that are helpful but can be reused then it is simply a useless device. Therefore our priorities should be made around these constraints of reliability first, sustainability second.

4.2.5 Practicality and Preference

As mentioned in the previous section 4.2.4 our product is intended for consumers and is intended to be convenient. When a product is convenient it is normally practical. This practicality constraint is one that we want more than most because we are creating something that is targeted towards typical consumers and a massive consumer base. Because of this it's important to value practicality when designing our device.

Practicality can be impacted many ways but for our project the largest impact on practicality would be intrinsically tied to the devices ability to be reusable. In the event that our device does manage to be reusable it will need to be cleaned by the end user. Cleaning anything requires care but our device is a small electronic one that needs to operate with a relatively high accuracy which makes the cleaning process even more specific and careful unless we can design a product that is extremely robust. This cleaning will hurt our project's practicality and become a very large hurdle for us during the design phase. We need to utilize design practices that favor device health, protection and reliability in order to reduce the cleaning effort required by the end user to improve its practicality.

Practicality also affects our product's design and how its reusability is implemented. If our device is one that is compatible with off the shelf menstrual pads it is practical in the aspect that the user does not need to purchase a brand they aren't comfortable with but it would require user installation. User installation is something we should try to avoid or simplify as much as possible. Complicated user installations can lead to poor reliability, accuracy, and practicality. If our device is instead designed to be implemented into a new reusable pad then we benefit from the fact that the user does not need to install the device but suffer in other aspects.

Our sponsor, Gabriela Mercado, mentioned in her presentation that reusable pads are unpopular with women and carry unhygienic connotations which hurts our project in

areas like user appeal and practicality. It also removes the comfort the user has in choosing which brand of pad they prefer. Many pads are designed in multiple different sizes and shapes depending on body type therefore if we were to choose a reusable pad design for practicality and reliability reasons it would mean we would need to produce many different sizes and shapes to better accommodate our user base.

Preference is a constraint that the product will struggle with. We are designing an electronic device with a transmitter and sensor that will be placed very close to the human body in an area that is sensitive. Most users will immediately be displeased with electronics being that close to their private areas and that will be a major hurdle this product has to overcome.

A possible way of overcoming this is to design the device in a way that hides much of the electronics, not to mislead our users but to make the product appear more user friendly and less scary. If our product integration goes the path of a device that fits into off the shelf pads then it will be much harder to hide the electronics.

On the other hand, if we create a fully reusable pad with the device embedded we can design it to appear much friendlier but at the cost of preference in the form of brand loyalty and disposition to reusable pads.

4.2.6 Health and Safety

Our project's design is of a device that is to be placed on the body as a wearable electronic device. Wearable electronics have become more popular in the last 2 decades with the rise of smartwatches and fitness trackers. Because of this there are many examples of how to design a product such that it stays wearable and usable while maintaining health and safety standards for the safety of the user.

The constraint our product faces in health and safety is the one that any other wearable fitness device would face but with the added difficulty being placed in a private, sensitive area of the body. We will need to be extra careful when it comes to making sure our device is healthy and provides safety to its user.

Common standards are in place such as RoHS and IPC-1752 that work to keep electronics safe for its users. These standards limit the amounts of lead, mercury, and other harmful materials that can be present in a device or component. Following these standards will be a must and purchasing components that follow these standards will also be a must if we want to keep our product safe for the user. The standards are a great way we can learn more about this and make our device safe but our product is not like most normal wearable electronics.

Our team will most likely need to take more measures to assure the user that the product is safe, this includes extra informational documents and references, exact handling requirements, easily available materials lists, product certification, and potentially test and study results that prove the product is safe. The device should be treated as if it were

an implantable device such as a pacemaker and follow the health and safety constraints and standards those devices adhere to because of the sensitive area our device will be and for the comfort of the user.

4.2.7 Manufacturability

Designing a feminine hygiene product with integrated electronics for leak detection presents several manufacturability constraints that require innovative solutions to ensure quality, safety, and cost-effectiveness. Integrating electronic components such as sensors, microcontrollers, and batteries into a thin, flexible, and absorbent product is challenging, as traditional hygiene products rely on flexible layers for comfort, making the addition of rigid electronics difficult.

Flexible, ultra-thin PCBs and low-profile components are essential to maintain a slim form factor without sacrificing comfort, while moisture protection is also crucial. Moisture protection for the electronics is another key consideration, as exposure to fluids could cause malfunctions. Applying a waterproof or hydrophobic coating by hand around sensitive areas like the sensors and battery can provide adequate moisture shielding.

Pre-coating critical electronic parts before assembly is also an effective strategy when manufacturing each unit individually. Encapsulation materials, like waterproof resins or heat-shrink tubes, can add further protection while remaining manageable for hand assembly. Battery integration introduces further challenges, as batteries in close contact with the body need strict safety measures to prevent overheating or leakage.

This was one of the reasons that we chose to go with a coin cell battery, as it is a lot safer. Testing and quality control are also important, even for a single unit. We will conduct a thorough manual inspection of each electronic component and perform functionality checks to ensure everything operates as intended. This step will involve testing the sensors and confirming that the battery is correctly connected, which adds to the overall reliability of our product.

Integrating electronic components such as sensors, microcontrollers, and batteries into a thin, flexible, and absorbent product demands careful component placement. Precision is essential, as even minor misalignments can affect the performance of the sensors and the comfort of the product. We must ensure that each component fits snugly within the absorbent layers without creating any bulk, which could make the product uncomfortable to wear.

Finally, creating a durable, flexible assembly by hand requires selecting appropriate adhesives or bonding techniques that don't add thickness. Medical-grade adhesives or manual lamination with thin, absorbent layers can keep the product cohesive without compromising flexibility.

CHAPTER 5 - LEVERAGING AI PLATFORMS FOR THE EASE PROJECT

5.1 Introduction

In recent years, artificial intelligence (AI) tools have become indispensable resources in various industries, including engineering. The ability to generate human-like responses, provide feedback, and assist with complex and advanced tasks revolutionized how students and professionals approach problem-solving. With the rise of several AI-based tools, such as ChatGPT, writing documentation and reports saw major changes in the way they were often created or supplemented. For Senior Design projects, these tools offered invaluable support but also had the potential to hinder the originality behind ideas or problem-solving.

This chapter explores the limitations, pros, and cons of ChatGPT and similar AI-driven platforms, and how these platforms compare in assisting with different aspects of the Senior Design process. It also examined how AI-based platforms could benefit or harm the learning experience. The goal was to assess how these platforms contributed to project development, documentation, and problem-solving.

Artificial intelligence tools had their limitations. In some cases, prompters encountered inaccurate or overly generalized responses. Understanding the possible limitations associated with artificial intelligence, while maintaining an appreciation for its strengths, helped students maximize the benefits AI provided in a project-based learning environment. Different platforms provided their own limitations and strengths, so it was a good idea to compare resources to see which tool best fit a specific need. The beauty was that multiple platforms could be used in conjunction, each serving as a different tool for a different need, but it was important to remember the limitations and risks associated.

5.2 Application in the EASE Project

The EASE Senior Design project encompasses quite a bit, including coding, hardware, documentation, data-analysis and brainstorming. In order to justify using an Artificial Intelligence based platform, we ensured that the platform fit one of our needs and helped aid our work and learning experience in an ethical way. A common choice for AI-based platforms is ChatGPT. ChatGPT works in most use cases but lacks native integration with hardware and coding platforms. ChatGPT does excel in understanding natural language prompts and responding in such a manner. In this section, we compare ChatGPT to other platforms to decide which platforms could have benefited us in our use case when originally planning for our project.

In order to effectively compare ChatGPT to similar AI-driven platforms such as Google Gemini, Claude, and GitHub Copilot, it is important and essential to establish clear

criteria that we will be comparing over. These criteria will guide the comparison and ensure that each platform's strengths and limitations will be assessed in a structured and meaningful way. The criteria for comparison will focus on key aspects that were critical to our Senior Design project, such as usability, performance, accuracy, cost, integration with engineering tools, and ethical considerations. The results of this comparison highlight strengths, weaknesses, and limitations of each artificial intelligence based platform and how they can possibly aid (or harm) our learning experience.

5.2.1 Evaluation Criteria

Identifying clear evaluation criteria is essential for making informed and objective decisions in any design process. Evaluation criteria serve as measurable benchmarks that help compare options, assess performance, and determine whether specific goals and requirements are being met. In the context of electronics or product development, these criteria might include factors like cost, efficiency, durability, usability, or compatibility. By establishing well-defined standards early on, teams can ensure consistency, reduce bias, and streamline the decision-making process, ultimately leading to more successful and reliable outcomes.

5.2.1.1 Usability and Interface

One of the most important aspects to evaluate is the usability and interface of each platform. This criterion shows how easy it is for a user to interact with a given artificial intelligence platform. In the context of our Senior Design project, a platform that offers a clean, intuitive interface allows for quicker learning and efficient use. The interface provides great insight on a platform's usability as a simplified, clear, and robust interface will provide the most usability, however, more advanced, complex interfaces provide better usage for other instances.

For example, ChatGPT offers a conversational interface that is straightforward, while Jasper AI for instance, offers a structured template, which can be helpful for creating formal documentation. In our comparisons, we will discuss the usability and interface for each similar artificial intelligence based platform to highlight associated strengths and limitations.

5.2.1.2 Responsiveness and Output Quality

Another important aspect to evaluate is the responsiveness and output quality. Responsiveness and output quality measures how quickly and accurately each platform delivers results. For our Senior Design project, it is essential that the platform, if used, will generate responses that are not only fast, but also relevant and precise. Different AI-based platforms vary in this aspect. For instance, ChatGPT excels at generating creative ideas and brainstorming solutions, while something like GitHub Copilot is better at giving coding suggestions, debugging, and autocompletion in real-time. Each platform's ability to offer coherent, concise, and accurate responses affects its utility in a Senior Design project environment where precision is key.

5.2.1.3 Integration with External Tools

Our Senior Design project involves varying components such as different hardware and compatible softwares, so evaluating an artificial intelligence based platform on the integration with external tools is logical. This criterion looks at how well the AI-based platform can work alongside engineering tools such as one of the IDEs, or MATLAB or other possibly used software or development environments that each serve a specific goal. ChatGPT, for instance, supports code generation, but it lacks native built-in integrations for real-time execution unless it is also paired with external tools. By contrast, GitHub Copilot integrates smoothly with an IDE such as Visual Studio Code to help in real-time with code completion and during the code execution. We have to understand our external tools and their use cases in order to determine how artificial intelligence based platforms can best aid those needs through possible integration.

5.2.1.4 Cost and Accessibility

Cost and accessibility plays a major role highlighting strengths and weaknesses of platforms. Some platforms such as ChatGPT, have limited free plans, and more advanced features sitting behind a subscription paywall, whereas other platforms such as Jasper AI require a paid subscription for full access. For students managing limited budgets, platforms that offer free tiers or student discounts may be a more alluring offer and play into a platform's strength if the discounted tier offers a high value. In cases where free tiers frustrate and work poorly, it reflects poorly on the platform as a whole because it does not entirely excite someone to spend money on a higher tier if results cause enough frustration, which can play into a platform's weakness.

When considering a platform a student may be wary of a platform's limitations and weakness and consider them strongly when deciding to pay for the platform. Additionally, the availability of platforms on different devices (e.g., desktop, mobile) should be considered when evaluating a platform's accessibility.

5.2.1.5 Ethical Considerations

A critical criterion to consider when comparing platforms are the ethical considerations. This includes evaluating how well each platform handles issues related to plagiarism, data privacy, and responsible use of artificial intelligence. For example, while ChatGPT offers useful responses and suggestions, it's crucial to properly cite AI-generated content to avoid academic misconduct. Some platforms also provide better transparency regarding data collection, making the platforms more suitable in environments where privacy is a priority.

5.3 ChatGPT Overview and Analysis

This section evaluates ChatGPT as an AI-based platform, analyzing its usability, output quality, integration with external tools, cost accessibility, and ethical considerations for

the EASE Notifying Feminine Hygiene Page project. The goal is to take away strengths, weaknesses, and limitations on ChatGPT to see how it can possibly help or harm our Senior Design learning experience.

5.3.1 Analysis Based on Criteria

The following sections provide a thorough analysis of AI platforms utilizing the evaluation criteria previously identified.

5.3.1.1 Usability and Interface

ChatGPT provides a conversational, user-friendly interface that allows users to prompt in a natural format, making it highly accessible for multitudes of users, even those without a technical background. The platform's simple structure allows for easy navigation, with no need for advanced configuration or installation. During our Senior Design project, the EASE project, ChatGPT can be used to generate ideas in order to brainstorm starting places to work with, to help give guidelines and outlines, and to help explain concepts we may otherwise not have a full grasp over.

In order to send a prompt, a user will “message” ChatGPT and it will give a response. ChatGPT saves chat history and conversation history so that previous chats can be recalled and reused, and uses conversation history to refer to previous prompts, replies, or information. The platform separates the chat into the following categories: Today, Previous 7 Days, Previous 30 Days, Previous 60 Days, and Older Conversations.

The free and paid interface does not differ greatly and usability is about the same, limited only on the speed and number of responses ChatGPT can give at its fastest tier speed, which is presently ChatGPT 4o.

5.3.1.2 Responsiveness and Output Quality

ChatGPT’s response time is nearly instantaneous, offering suggestions within seconds. For general inquiries like explaining a topic or troubleshooting code, ChatGPT can provide high-quality responses, although some queries may require further refinement for a more desired or precise response. In the context of the EASE project, the platform can generate brainstorming ideas or to clarify topics or information we find, and the output quality depends on how useful we find the generated response. ChatGPT does respond well to each prompt but refinement is often needed.

5.3.1.3 Integration with External Tools

ChatGPT is primarily a text-based platform, so its ability to directly integrate with external tools such as development environments or hardware is limited. While it can generate code or help guide through technical concepts, real-time testing or interaction with engineering software requires additional manual input.

During our Senior Design project, ChatGPT can be used to help guide the coding process as well as the hardware handling process for general techniques, though we will have to interact more hands on due to the lack of native integrations. This is beneficial to our learning experience because it forces us to learn our topics better without relying on a third-party source but it may still become something a student can be dependent on. The lack of native integrations definitely puts other platforms with native integrations have extra resources that ChatGPT lacks, giving it a strong limitation.

5.3.1.4 Cost and Accessibility

One of ChatGPT's key strengths is its accessibility. With a free-tier option and the fact that prompts can be given in a natural language, sets the platform up for being highly accessible, making it ideal for educational purposes. Premium features offer more enhanced response quality, which is not necessary for the Senior Design project, however the design group has full access to its premium suite.

5.3.1.5 Ethical Considerations

Using ChatGPT in an academic or professional setting requires some ethical considerations. Although this AI-based platform can serve as a strong, useful tool, it can also cause consequences for misuse. Using ChatGPT in an academic or professional setting requires careful attention to ownership and citation as well as data privacy, as crucial private information should not be given. ChatGPT does not natively provide citations leading to common cases of plagiarism; however, with ethical consideration, ChatGPT can be shown to be quite the powerful tool.

5.3.2 Strengths

Based on the analysis above, several strengths of ChatGPT standout:

- Ease of Use: The conversational interface allows users to interact with the platform effortlessly, enabling even non-technical users to benefit from its capabilities.
- Rapid Response: ChatGPT's near-instantaneous response time improves productivity, particular during brainstorming or drafting stages.
- Free Accessibility: ChatGPT offers sufficient features in its free version, making it highly accessible for students and for educational projects like EASE that are limited on budgets.
- Broad Utility: It is capable of providing general guidance across a range of topics, from code generation to technical explanations, which is beneficial for hardware and software design aspects of the Senior Design project.

5.3.3 Weaknesses and Limitations

Based on the analysis above, ChatGPT presents several limitations:

- Lack of Integration with External Tools: While useful for idea generation and code assistance, it cannot directly interface with engineering software or simulators, nor any hardware, limiting its functionality in highly technical tasks or tasks that require real-time interaction.
- Generalized Knowledge: ChatGPT may struggle with domain-specific technical knowledge, offering generalized answers that may require further refinement, research, or validation.
- Inconsistent Accuracy: Although generally accurate, responses are not guaranteed.

5.4 Comparison with Similar Platforms

In this section, we will be comparing the different options for AI-based platforms under the same criteria we analyzed ChatGPT with to highlight different strengths, weaknesses and limitations. The goal is to see if other AI-based platforms can help or hard the Senior Design project experience in ways ChatGPT cannot already.

5.4.1 GitHub Copilot

5.4.1.1 Overview

GitHub Copilot is an AI tool specifically designed to assist in real-time coding by offering code suggestions, auto-line completion, and completing code blocks within integrated development environments like Visual Studio Code.

5.4.1.2 Analysis Based on Criteria

GitHub Copilot excels in technical coding assistance, offering real-time code completion and suggestions based on context. It integrates directly with coding environments, such as Visual Studio Code making it extremely valuable and easy to use for a development task. Customization is possible which increases accessibility, but a coding basis is needed to understand its full strength.

5.4.1.3 Strengths, Weaknesses, and Limitations

Strengths: GitHub Copilot's strength lies in its seamless integration with IDEs such as Visual Studio Code, and its ability to generate relevant code snippets, making development faster and more efficient.

Weaknesses: It sometimes generates suboptimal or incorrect code, making it not entirely reliable and requires the user to have enough coding knowledge to catch possible mistakes. It also heavily relies on user input for context.

Limitations: GitHub Copilot focuses exclusively on code-related tasks and doesn't provide a broader functionality outside that type of development limiting its usefulness for tasks such as documentation and hardware support.

5.4.1.4 Conclusion

GitHub Copilot is a valuable tool for speeding up coding tasks in the Senior Design project. Our Visual Studio Code is integrated with it; however the IDE we will likely use for embedded development, such as Arduino IDE is not. While this platform lacks versatility outside of coding, it complements ChatGPT's broader knowledge base by providing hands-on technical assistance in the coding process.

5.4.2 Microsoft Copilot

5.4.2.1 Overview

Microsoft Copilot is integrated into Microsoft 365 and assists with automating tasks across the Office suite, including Excel, Word, and PowerPoint. It also integrates with tools like Visual Studio for coding assistance.

5.4.2.2 Analysis Based on Criteria

Microsoft Copilot is highly integrated with Microsoft products, making it ideal for tasks like documentation, data analysis, and report generation. However, its development assistance, while useful, is secondary to tools like GitHub Copilot. It also does not have as broad of a scale as ChatGPT.

5.4.2.3 Strengths, Weaknesses, and Limitations

Strengths: It has strong integration with Microsoft's productivity tools making it a valuable tool for managing project documentation, presentations, and sheets.

Weaknesses: While it offers some coding support, its ability is overshadowed by strong technical AI-based platforms such as GitHub Copilot. It is not as specialized in development environments.

Limitations: Its usefulness is primarily within the Microsoft ecosystem, limiting its application in non-Microsoft tools or in a more technical, specialized development environment like that in Senior Design.

5.4.2.4 Conclusion

Microsoft Copilot is an excellent tool for managing the non-technical aspects of the Senior Design project such as the documentation; however, for more technical tasks like hardware support and coding it suffers.

5.4.3 Google Gemini

5.4.3.1 Overview

Google Gemini is Google's AI platform designed to handle a wide range of tasks from data analysis to natural language processing. It integrates well with Google's cloud services and productivity tools.

5.4.3.2 Analysis Based on Criteria

Google Gemini offers strong capabilities for data management and analysis, which could be useful for any aspects of the Senior Design project that requires some analytics. However, it lacks the specific technical development support seen in ChatGPT or GitHub Copilot.

5.4.3.3 Strengths, Weaknesses, and Limitations

Strengths: Google Gemini has a strong integration with the Google workspace and its cloud services, making it an excellent platform option if using the Google bundle for collaboration, data analysis, and task automation.

Weaknesses: The platform is not optimized for coding tasks or advanced, technical problem solving tasks, which greatly reduces its use case for our Senior Design development which is quite technical.

Limitations: Google Gemini focuses more on high-level task automation and cloud-based services, limiting its direct impact on technical, hands-on project work.

5.4.3.4 Conclusion

Google Gemini is a valuable artificial intelligence based platform for handling collaboration and data heavy tasks but it lacks the coding assistance and advanced problem solving skills needed for a technical project like EASE. The platform can be used to complement ChatGPT in managing project data and communication, but it cannot serve as a direct replacement due to the technicality required.

5.5 Evaluation of Useful Platforms

The comparison of differing artificial intelligence based platforms shows that each platform offers different strengths and limitations when applied to the Senior Design learning experience.

- ChatGPT stands out for its versatility and ease of use, giving a vast utility across a range of tasks, from brainstorming to providing technical explanations; however, its limitations in integrating with external tools or delivering domain-specific knowledge suggests it cannot fully meet the technical needs of our Senior Design project.
- GitHub Copilot excels in code generation and auto-completion, making it ideal for development tasks in coding-intensive projects. However, its focus on coding means it lacks a broader functionality offered by ChatGPT for non-coding tasks.

- Microsoft Copilot is well-suited for managing non-technical tasks such as documentation and project management, but it struggles to provide the technical depth necessary for complex coding or hardware-related tasks.
- Google Gemini is powerful for data analysis and task automation, but like Microsoft Copilot, its strengths lie outside of direct technical development assistance.

In essence, while no single platform meets all the demands of a Senior Design project, combining tools like ChatGPT for conceptual guidance, GitHub Copilot for coding, and Google Gemini for data handling, can enhance the overall learning experience. Each tool serves a different purpose, and leveraging them in conjunction ensures that the weaknesses of one platform are compensated by the strengths of another.

5.6 Examples of Platform Use in EASE Project

To illustrate how these AI platforms could have been applied in the EASE Senior Design project, this section provides specific examples for ChatGPT, GitHub Copilot, and Google Gemini, demonstrating their utility, benefits, and associated risks.

5.6.1 ChatGPT: Brainstorming and Clarifying Concepts

5.6.1.1 PCB Technology Comparison

One example of ChatGPT being used in the development of this project was in researching the various PCB technologies that exist. This project necessitates an electronic device be built that is capable of detection and transmission while also meeting the project's constraints. Utilizing ChatGPT quickly provided us with an extensive preliminary list of individual PCB technologies to focus our research, as shown in [\[A-1\]](#). In analyzing the response provided with ChatGPT, the platform provided a very surface level understanding of each technology, briefly highlighting primary uses, giving a small insight as to the benefits and drawbacks of each technology.

The preliminary list was then used as a guide as to what to research within various reputable resources including industry guides, engineering standards, and manufacturing sites. Upon comparing the response generated by ChatGPT and the knowledge acquired through research, the surface level description generated by AI was reasonably accurate but failed to provide a well rounded understanding of uses, advantages, disadvantages, attributes, effectiveness, efficiency, and cost which could only be obtained through in depth research. These technical metrics were necessary to provide a well informed decision as to which PCB technology was best to fulfill the requirements of this product.

This example exemplifies both the usefulness and the limitations that ChatGPT can provide in conducting the technical research required for this project. ChatGPT can provide vast amounts of information within seconds of providing a prompt, which can provide some general direction and guidance of existing ideas and concepts which aid in the initial research process. However, ChatGPT cannot (and should not) be the only

resource used to make critical decisions or conclusions as it is not likely to provide the necessary technical data and statistics for such, and will only provide surface level overviews that may vary in accuracy.

5.6.1.2 Battery/Power Supply Technology Comparison

Another example of ChatGPT being used in the development of this project was in coming up with ideas for how to power the device. It was useful for accelerating research, in that it gave us potential options to explore. After researching some of the options given by ChatGPT, it was obvious that some of the options given were either experimental, expensive, unrealistic, or out of the scope of the project, as shown in [\[A-4\]](#).

This was one of the drawbacks of using ChatGPT. To counteract this limitation, we asked it to give us options that were accessible to anyone. As ChatGPT is still an emerging technology, it is important to be skeptical of its results when doing research. It is useful as a way to get started, but should never be fully trusted to give you accurate results.

5.6.2 GitHub Copilot: Assisting in Code Development

One example of GitHub Copilot being used in the development of the EASE project was in assisting in code development. This project requires software to notify when the transmitter sends a message to notify the user and to help calculate the current threshold a sensor is measuring to check if it has reached the 95% capacity mark.

Using GitHub Copilot we can get live suggestions based on our code, from within our IDE or from their webpage. Certain IDEs like Visual Studio Code have built-in integrations with GitHub Copilot, but other IDEs like Arduino IDE do not natively have that integration.

Depending on the IDE used at the time we could use the GitHub Copilot Chat option or temporarily (or permanently) write our code in an IDE that has native integration with Copilot. Utilizing GitHub Copilot, we can quickly set up the framework for a file we will be working in, as shown in example [\[A-2\]](#).

After analyzing the response from GitHub Copilot, we can see that the platform provided the basic framework along with some comments to help base off the specific Arduino MCU based development. This framework should then be compared to the C++ framework Arduino IDE provides in their built-in board specific templates found directly on the IDE. You could also run the framework to see what type of build errors incur to see the accuracy of Copilot.

The example shows the possibilities opened by using GitHub Copilot but it also demonstrates the risks attached with code that is either wrong, or unoptimized for the desired use case. Comparing the code output provided by Copilot with other sources or your own personal knowledge of that coding language is the best practice to ensure minimizing any harmful or unhelpful outputs when using this AI-based platform.

5.6.3 Microsoft Copilot: Assisting in Table Production and Research Insight

An example of Microsoft Copilot being used in this project is when creating tables and making comparisons between sensor options. When researching sensor options for this project our main goal is not to look for specific parts but instead sensing methods and methodologies. We want to take inspiration from these sensors and hopefully design our own sensor which can work for our project. Because of this it became challenging to create a table comparing the sensors because none of them were going to be used but instead they would be inspiration. Microsoft Copilot was a great tool here to compare the sensor options and implementations and hopefully create a graph that more informed our decision when picking a sensor type and method, as shown here [\[A-3\]](#). The data it used to populate the table was clear and understandable but contained too much information so I cut down the table and took only the categories we would be most interested in when working on our project.

This is a good example where a tool like this can be used to collate the data and information gathered in research and create a useful summary and expression of that data. This expression can then be used to come to better conclusions and inform your decision when working on a project.

CHAPTER 6 - HARDWARE DESIGN

The following sections describe multiple iterations of various hardware designs utilized. Three versions are described, as the first two iterations encountered significant performance issues for various reasons. All are described below.

6.1 Hardware Design V1

The following section outlines the initial theoretical hardware design. After initial prototyping, testing, and advising from Dr. Weeks, other hardware designs were pursued to maximize efficiency as well as prototyping potential that matched the skill set of our team.

6.1.1 Power Supply (Both External and Internal)

The initial power supply for this project was a compact system due to the small amount of peripherals and components that are being used and the more infrequent nature of our power usage. For the power source we initially used a coin cell battery. This 3V works fine on its own for our MCU due to how we had it set up. Our MCU had its own internal DC-DC voltage regulator that outputs on the DCDC_SW pin (pin 17), meaning that we

could connect it directly to the MCU without any issues and we would not even need to change our configuration. However we instead chose to add an external boost converter that would increase the coin cell's voltage to 3.3V and connect that to the MCU using a configuration that would use the internal DC-DC converter.

The reason we did this is to keep a consistent voltage supply that both our sensors and MCU could use. The capacitive sensor we are using requires an input voltage of 3-3.3V and we chose to operate on the higher side to keep safe but after testing battery life and power consumption we will most likely change that value closer to 3V. When powering the MCU using the internal voltage regulator we need to make sure our configuration is correct and the correct pins are tied together.

Typically the main logic unit is going to be powered via the VDDR pins, when using an external voltage regulator you would supply this directly and the voltage would be around 1.7-1.9 according to TI. Because we are using the internal DC-DC regulator we need to power that first through the VDDS_DCDC pin (pin 18). That node can then also be connected to the other VDDS pins around the MCU (pins 11 and 28). The internal voltage regulator output is then on pin 17 which we can connect to the VDDR pins but with the exception of an inductor between the nodes to reduce noise and keep a more stable voltage. A capacitor is tied to it, then also used to reduce AC noise. The MCU supply configuration used is one of the recommended power supply implementations listed in our MCU's datasheet [\[Data-1\]](#). The capacitive sensor circuit is powered by the external DC-DC boost converter and the solid state sensor electrodes are set up in a matrix array alignment meaning they are directly powered by the MCU's GPIO pins. For the matrix we did not need high drive capabilities therefore we did not need to constrain the placement. Figure 6.1.1 provides the schematic of the boost converter circuit while figure 6.1.2 provides the MCU schematic and associated power distribution.

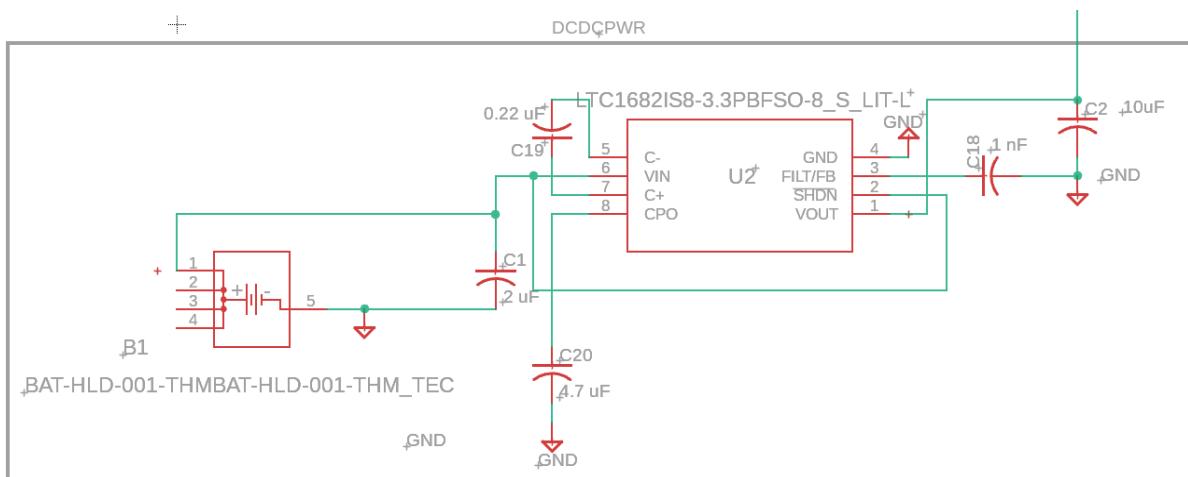


Figure 6.1.1 Schematic of the boost converter circuit (created in Fusion 360 by Authors)

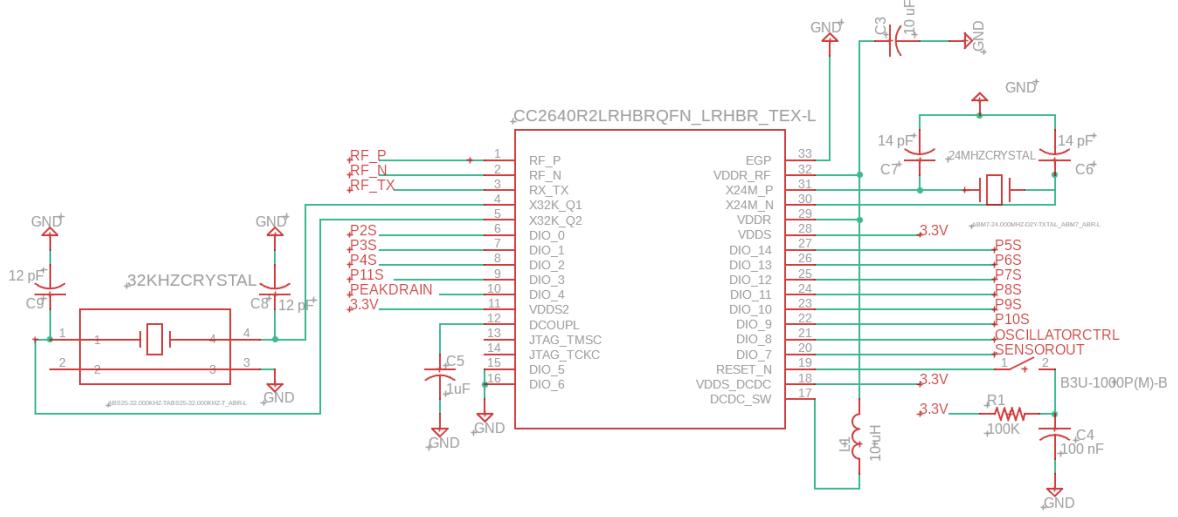


Figure 6.1.2 Schematic of MCU configuration including power distribution (created by Authors in Fusion 360)

6.1.2 Capacitive Sensor Circuit

The first capacitive sensor circuit used a configuration very similar to the capacitive sensor we purchased and tested. For our project we wanted to keep as much as possible on a flex pcb to improve comfort which gave us the idea to port the original sensor design onto our main pcb.

A capacitive sensor circuit is relatively simple. VDD is taken from our external voltage regulator and passed through a 555 timer circuit to produce a 50% duty cycle square wave oscillator. The design is referenced from this website on 555 timer configurations [59]. It is not an astable oscillator because we control the RST pin via a MOSFET tied to a GPIO pin. This square wave is then fed to an RC low pass filter circuit. In this circuit the capacitor is our capacitive sensor. The capacitance is controlled by the dielectric constant of the dielectric in between the capacitor plates and the area of that dielectric.

The dielectric constant of air is roughly 1 and the dielectric constant of water is around 80 times higher. This means if water is present inside the electric field it will result in the capacitor having a higher capacitance resulting in the square wave to have a lower peak to peak output voltage. This filtered square wave is then fed to a peak detector circuit which will capture the peak as a voltage on a capacitor. This capacitor can then be drained at any point using the MOSFET controlled by the MCU. This let us change the timing of the peak detector circuit which lets us modify the size of our sensor capacitor because we can control the timing of the peak detector discharge.

The only differences between the sensor we purchased and the first iteration of our capacitive sensor is the reduction of a voltage regulator circuit and the sensor capacitor. The voltage regulator was not used because we instead chose to use our own external

DCDC boost converter and the sensor capacitor was changed because we wanted to create our own sensor electrode flex pcb to control the size and placement of the electrodes. Figure 6.2.1 provides the logic block diagram for the capacitive sensing circuit while figure 6.2.2 depicts the associated schematic.

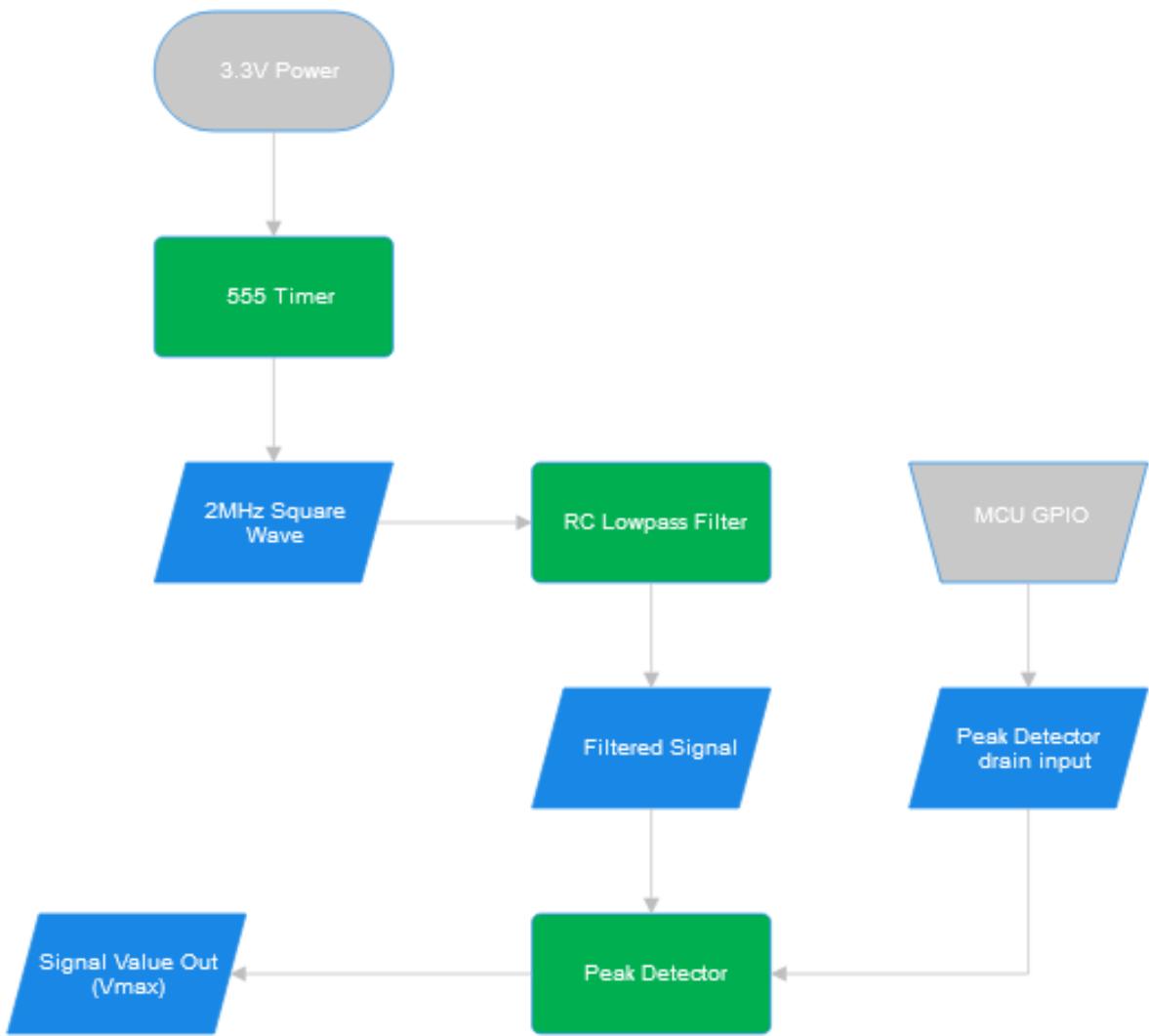


Figure 6.2.2 Capacitive sensor block diagram (created by Authors in SmartDraw)

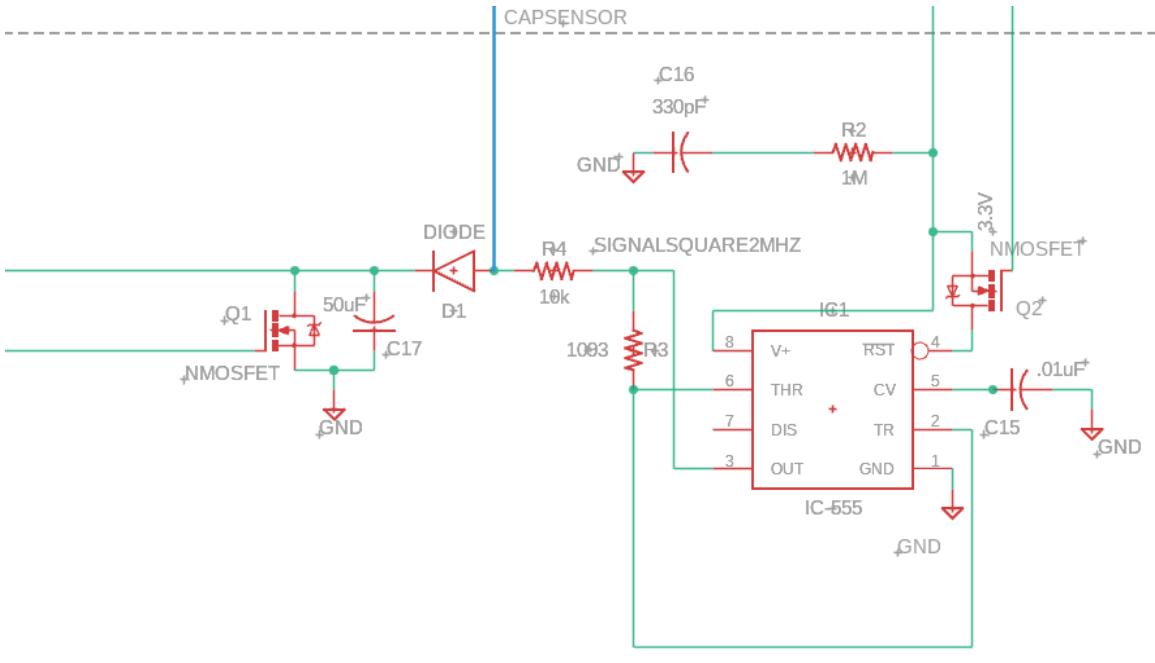


Figure 6.2.1 Capacitive sensing circuit (created in Fusion 360 by Authors)

6.1.3 Sensor Electrode Pad

The sensor electrode pad contains the capacitive sensor capacitor electrodes and the electrodes for the solid state matrix array. The schematic for this is barebones because the only components on the pad are a 12 pin ribbon cable connector, and the diodes needed for the matrix array. The electrodes on this pad are copper pours and can be seen more in depth in chapter 8 where the PCB design is located.

Important connections for this pad are the gpio pins required for the matrix array, the connections to the capacitive sensor circuit, and the central ground for shielding and proper capacitance values. Simple 10k resistors are added in series with the matrix array to ensure proper MCU health, we only need to determine a high or low signal so minor current is necessary here.

In the schematic the contacts for the matrix array are placeholder part, the B3U 1000P switch, on the PCB shown in chapter 8 you will be able to see the copper pad implementation for both the contacts and the capacitor electrode, a mask would be applied to the capacitor electrodes. Figure 6.3.1 provides the electrode pad schematic in a matrix array configuration.

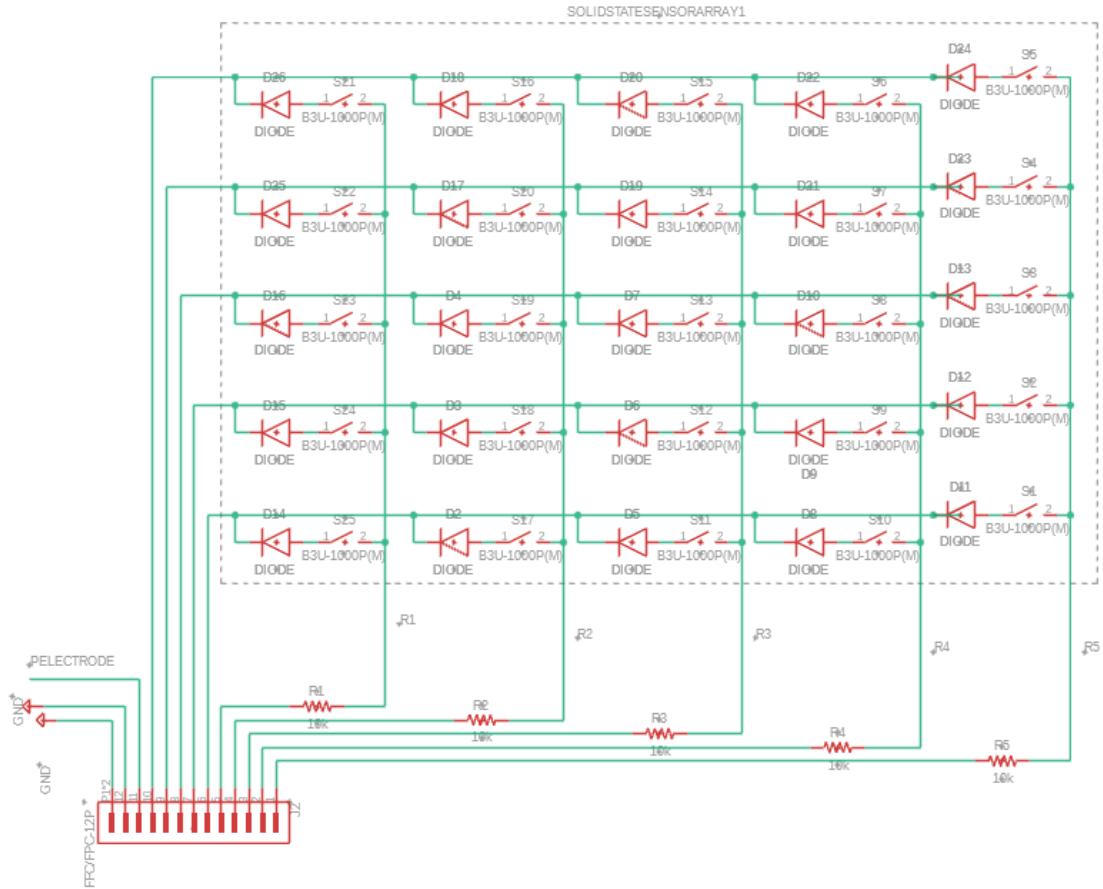


Figure 6.3.1 Electrode pad Schematic with matrix array configuration (created in Fusion 360 by Authors)

6.1.4 Transmission Circuit

The transmission circuit is another important part of the main PCB and MCU. Our intention is to use a PCB antenna for this project and for this using a PCB configuration for the transmission circuit is important. The TI MCU datasheet gives six examples of transmission configurations, differential (with and without internal bias), single ended (with and without internal bias), and single operation with two antennas (with and without internal bias). We did not want to use two different antennas to preserve size and single ends produce significantly worse performance than the differential configuration which led us to use TI's reference differential operation [\[Data-1\]](#) with internal bias configuration. We wanted to use a configuration with the best performance even if it meant more power consumption because we are still new to PCB design and wireless data transmission. Additionally, we also wanted as much room for error when using the transmission as possible. Figure 6.4.1 shows the transmission circuit we planned to use and how it connects to the MCU via the RF_TX, RF_N, and RF_P pins.

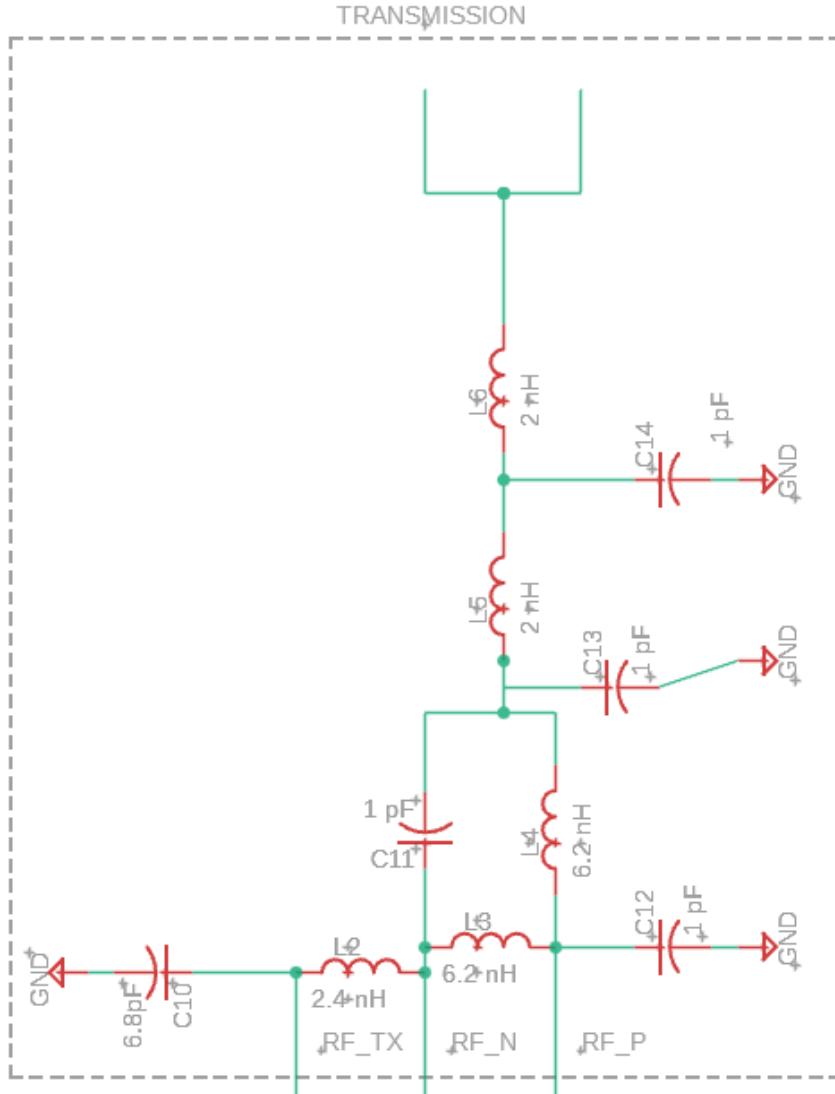


Figure 6.4.1 Transmission circuit schematic (created in Fusion 360 by Authors)

6.1.5 Crystal Oscillators

The last pieces of the schematic are the addition of two crystal oscillators for the MCU. A 32KHz crystal oscillator for the support of a real time clock (RTC), and a 24MHz crystal oscillator because it is necessary for radio operation and for its usage in communication modes like UART, SPI, and I2C. In the event that we wanted to add extra peripherals or use UART to debug our project the 24MHz clock would be very helpful. The connections for these oscillators are straightforward for the schematic. The MCU has dedicated positive and negative pins for the 24MHz oscillator and for the 32KHz oscillator the Q1 and Q2 pins on the MCU connect to pins 1 and 4 of the oscillator. For both of the oscillators these connection points should then include load capacitors in between them and ground. We followed TI's recommendation of 12pF for the 32KHz oscillator and used 14pF for the 32MHz oscillator to keep the crystal load capacitance in the middle of

the recommended values listed in the datasheet [\[Data-1\]](#) and [\[Data-4\]](#). Figure 6.1.2 provides a schematic of the MCU configuration with oscillators.

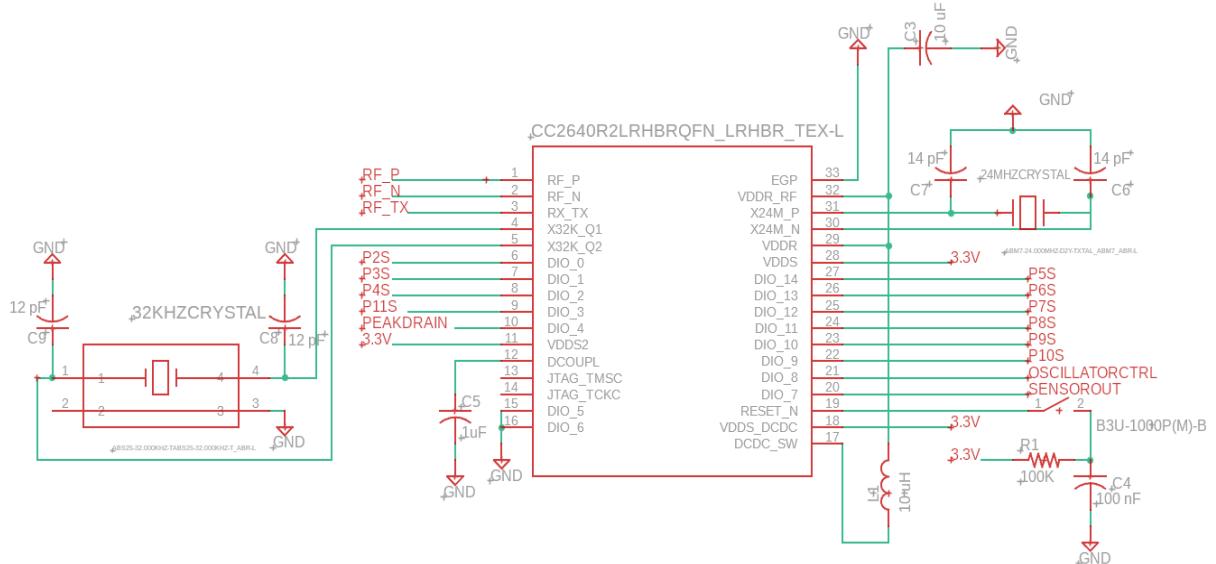


Figure 6.1.2 MCU configuration with oscillators (created in Fusion 360 by Authors)

6.1.6 Complete Integration

The project is split into 5 different subsystems. The MCU and its peripherals, the electrode pad and solid state sensor array, the transmission circuit, the power supply, and the capacitive sensor circuit. The solid state sensor array and electrode pad, which contains the capacitor for the capacitive sensor circuit, are separated from the other subsystems via the 12 pin ribbon cable connector. The separation of these subsystems from the rest of the system is to preserve space and to be able to have more control over the placement of the sensors. After testing it may become important to move the capacitive sensor circuit closer to its main capacitor electrodes in order to have more control over the noise a long trace would create. The following figure 6.6.1 provides the schematic for the fully integrated main PCB. The figure 6.6.2 gives more clarity as to how the subsystems should be interacting with each other based on the schematic provided in 6.6.1. Most of the logic that determines the state of the device will be from the MCU which will use data collected from the sensors to determine the volume of pad that is used which can then trigger an alert which will use the transmission circuit to be sent to the user.

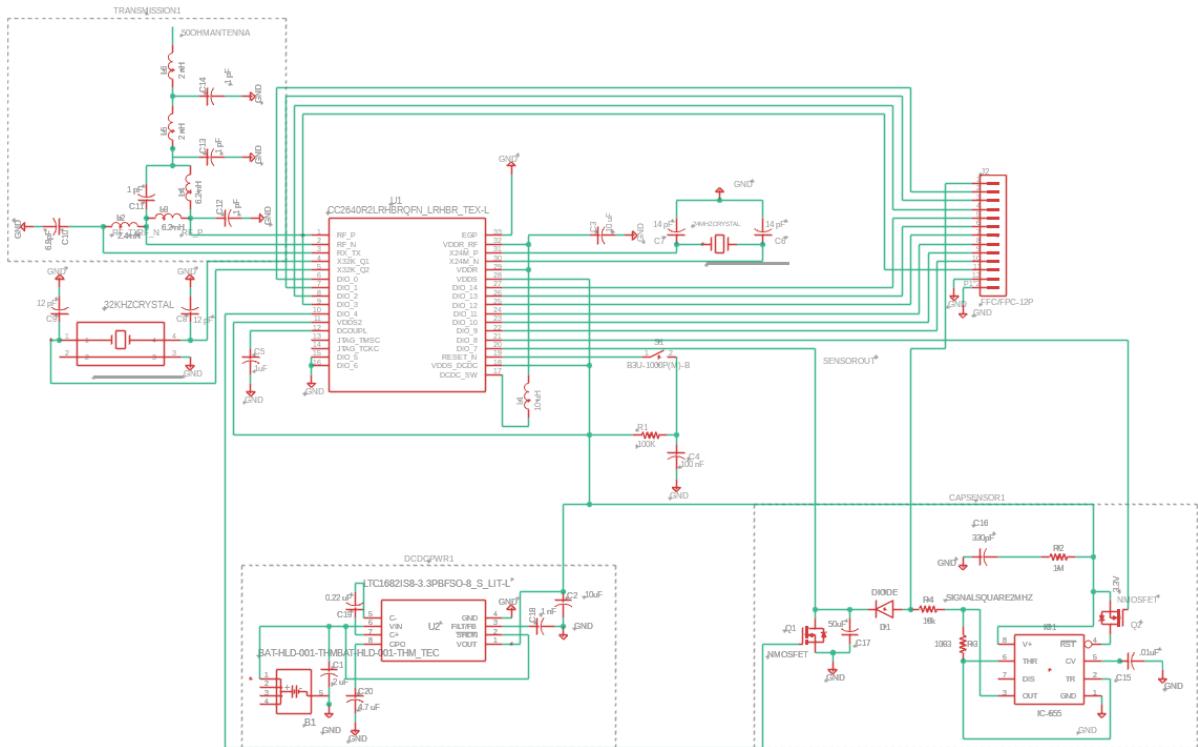


Figure 6.6.1 Overall schematic of main PCB (created in Fusion 360 by Authors)

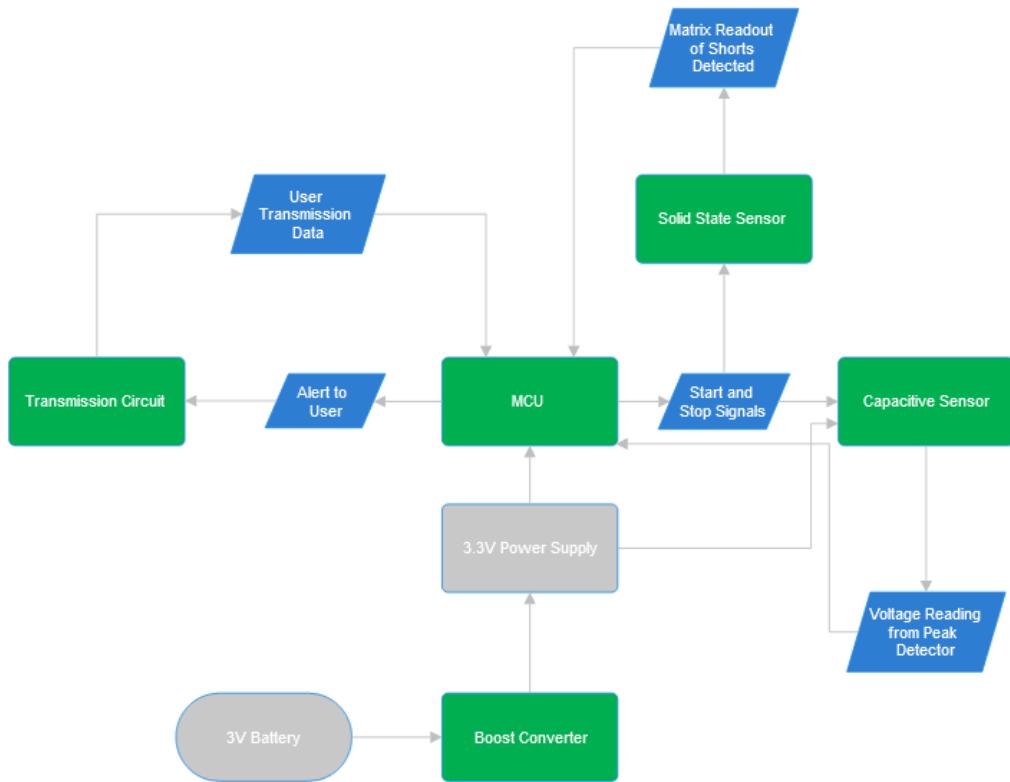


Fig 6.6.2 Hardware System Flowchart V1 (created in SmartDraw by Authors)

6.2 Hardware Design V2

As previously mentioned, our initial design of a capacitive sensor utilized a 555 timer to generate a square wave that would vary in amplitude for changes in capacitance rather than using a dedicated capacitance to digital converter IC. However, upon initial testing, the signal would experience significant overshoot which was heavily impacting the peak detector's signal. Because of this, we elected to switch the sensor design to utilize the capacitance to digital converter previously mentioned for a more accurate sensor reading. The capacitance to digital converter would also achieve much higher ranges of precision which is necessary when measuring small liquid volumes.

In addition to this, the ESP 32-WROOM was selected as the MCU for the design. This is because for prototyping the CC2640 is too small for our team to solder and would require an additional antenna or transmission circuit despite handling RF communication well. For ease of integration and troubleshooting in prototyping, the ESP32-WROOM-32 module includes the antenna and crystal oscillators and is large enough for our team to solder.

6.2.1 ESP32-WROOM Configuration

Datasheets were referenced to configure the ESP32-WROOM with corresponding peripherals and the USB to UART, utilizing the CP2102. With these references, the following schematics were designed.

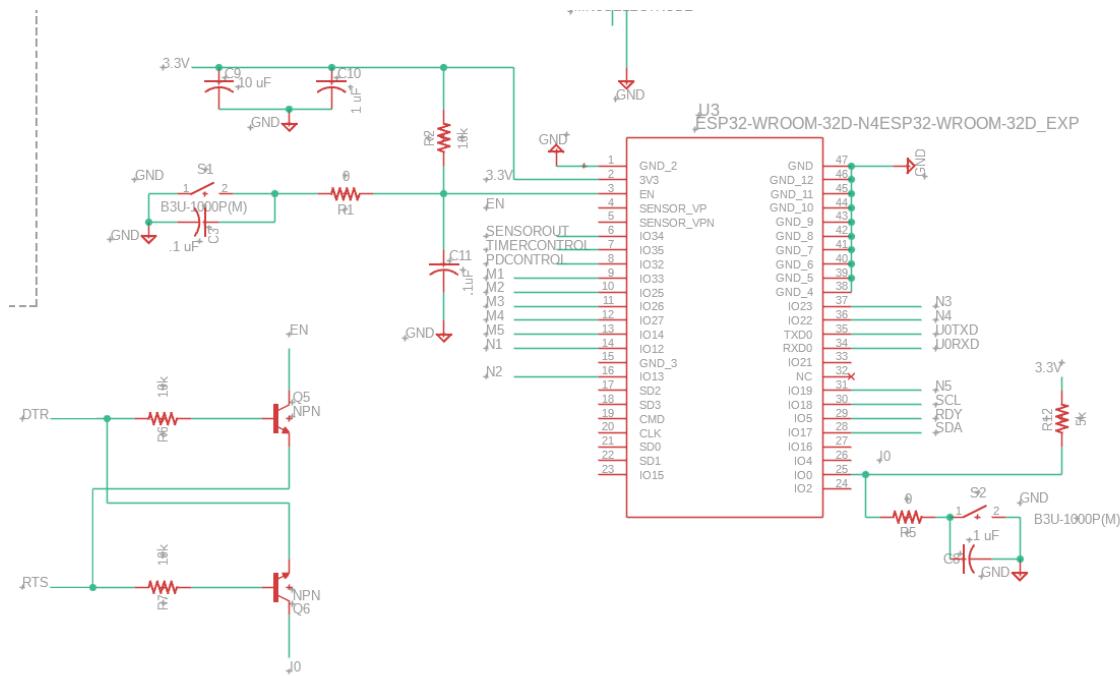


Figure 6.2.1.1 ESP32-WROOM Schematic (created in Fusion 360 by Authors)

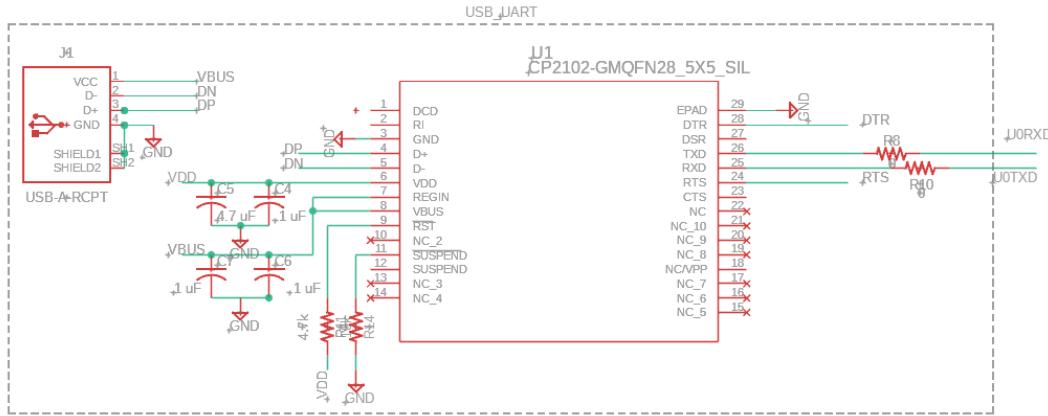


Figure 6.2.1.2 USB to UART Schematic (created in Fusion 360 by Authors)

6.2.2 AD7746 Extension Circuit

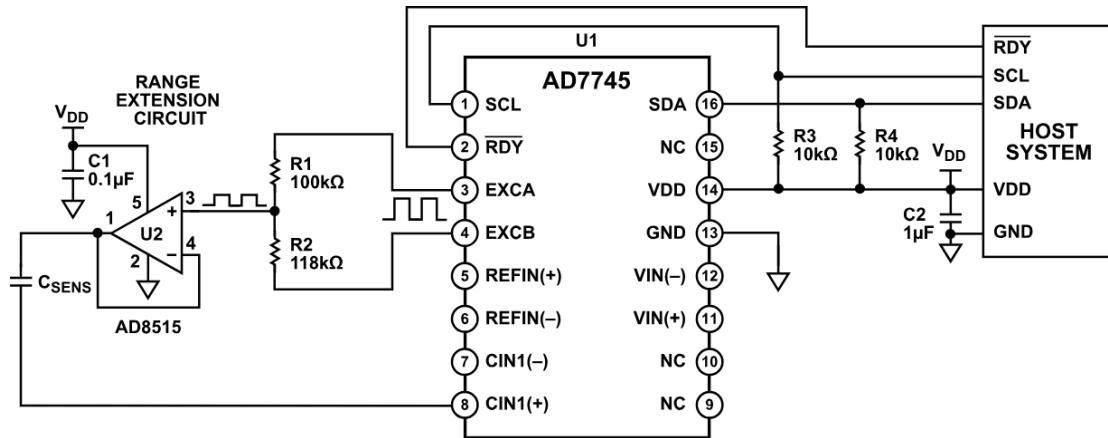
Upon measuring the base capacitance of the electrode pad PCB, it was determined that an extension circuit would have to be integrated as it measured 445 pF, which is well outside the base range for the AD7746. The Analog Devices application note AN-1585 presents a valuable solution for extending the input range of the AD7745 and AD7746 capacitance-to-digital converters (CDCs), enabling them to interface effectively with sensors exhibiting large bulk capacitance.

These CDCs are highly accurate, high-resolution devices designed for measuring small capacitance changes. However, their native input range of ± 4 picofarads (pF) can be limiting in applications involving sensors with significantly higher capacitance values, such as capacitive humidity sensors. This application note addresses this limitation by introducing a simple yet effective range extension technique based on excitation voltage attenuation [60].

The core idea of the range extension method is to reduce the excitation voltage applied to the sensor, thereby proportionally reducing the charge transferred during each sampling cycle. This attenuation allows the CDCs to handle larger sensor capacitance values without saturating the input. The implementation involves configuring the excitation sources (EXCA and EXCB) to be inverse signals and introducing a resistor divider network (consisting of resistors R1 and R2) to scale down the voltage. The resulting attenuated voltage is then used to excite the capacitive sensor [60].

To maintain accurate measurements and ensure proper charging of the sensor, an operational amplifier—specifically the AD8515—is employed as a buffer. This op amp delivers the attenuated excitation signal to the sensor while preserving signal integrity. The extension factor, denoted as F, represents the ratio by which the excitation voltage is reduced. For instance, if a sensor has a bulk capacitance of 200 pF and a sensitivity of

0.25 pF per percent relative humidity (% RH), the extension factor required would be around 11.76. This factor directly informs the selection of resistor values for the divider network [60].



08598-001

Figure 6.2.2.1 AD7746 Extension Circuit from Analog Devices

Additionally, the application note highlights the use of the on-chip CAPDAC (capacitance digital-to-analog converter), which compensates for the sensor's inherent bulk capacitance. This compensation allows the CDC to focus on measuring small capacitance variations superimposed on a large baseline. However, it is important to note that the CAPDAC's actual capacitance can vary slightly due to manufacturing tolerances, necessitating individual calibration for precise measurements [60].

After configuring and performing some initial testing, it appeared that the extension had a limit of 200 pF. Because of this, two parallel capacitors were placed in series to effectively reduce the overall capacitance of the sensor. Theoretically, it is advised to avoid manipulating the base capacitance in such a way, as it can negatively impact the digital outputs by saturating the capacitance. However, this design was properly breadboarded and was verified to effectively meet the necessary design requirements. The following presents the corresponding schematic for the modified design.

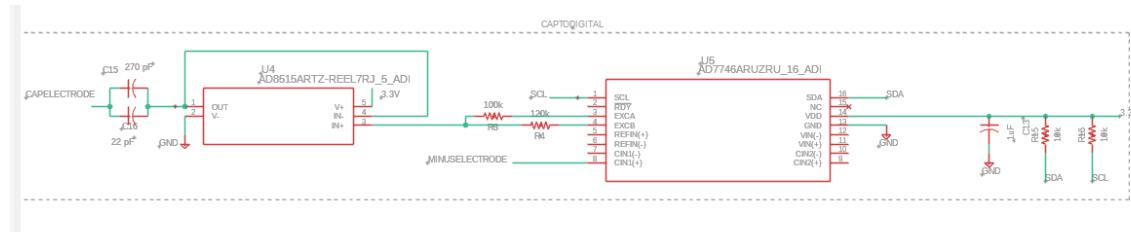


Figure 6.2.2.2 CDC Schematic (created in Fusion 360 by Authors)

6.2.3 Complete Schematic

Figure 6.2.3.1 below presents the fully integrated system, to include the voltage regulation, power supply, CDC, ESP32-WROOM configuration, and USB to UART circuits. Figure 6.2.3.2 depicts the corresponding flowchart.

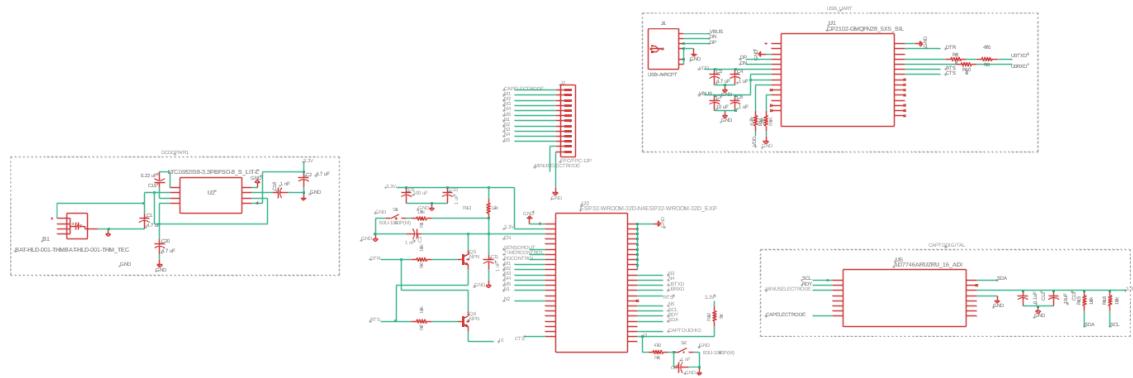


Figure 6.2.3.1 Integrated Schematic (created in Fusion 360 by Authors)

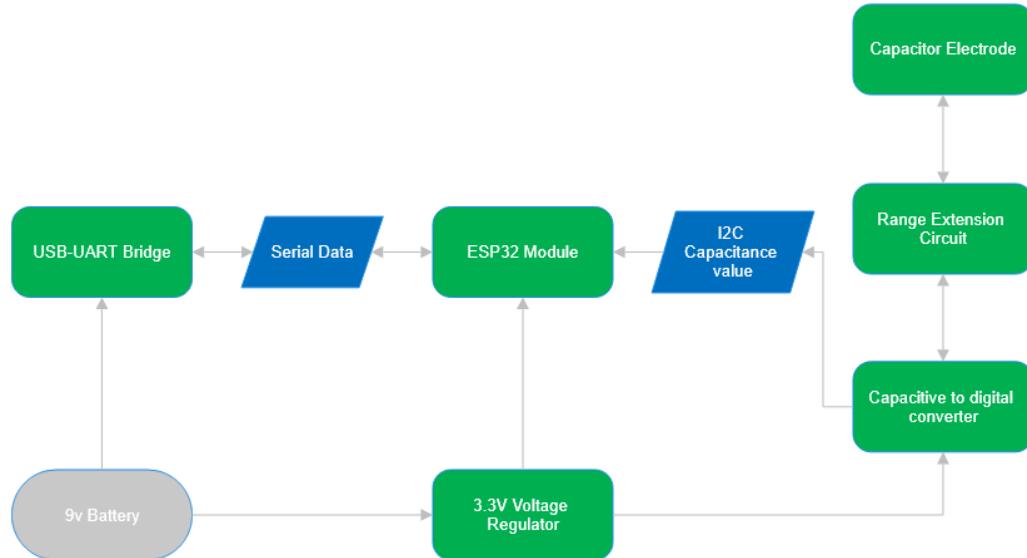


Fig 6.2.3.2 Hardware System Flowchart V2

6.3 Hardware Design V3

Despite a working breadboard prototype, the design of V2 encountered a major setback in which the digital output would be the maximum value when plugging in the electrode pad, despite proper design and CAPDAC configuration. This problem was associated

with parasitic capacitance within the main PCB that could not be troubleshooted while still adhering to the time constraints of the project. Because of this, a new design was proposed, utilizing a change in frequency of a 555 timer to correspond with a change in capacitance of the electrode pad. Since an inverse relationship exists between capacitance and frequency of the 555 timer, as the capacitance of the electrode pad increases with the application of fluid, the frequency of the 555 timer should decrease accordingly which can be utilized to correlate to the desired thresholds.

$$f_c = \frac{1}{0.639 (R_a + 2R_b) C}$$

C = Capacitive Input of Sensor

Equation 6.3.1 Frequency Output of 555 Timer

The following schematic in Figure 6.3.1 shows the configuration used for the 555 timer. This was designed on a breakout board. Figure 6.3.2 depicts the fully integrated system using the 555 Timer breakout board.

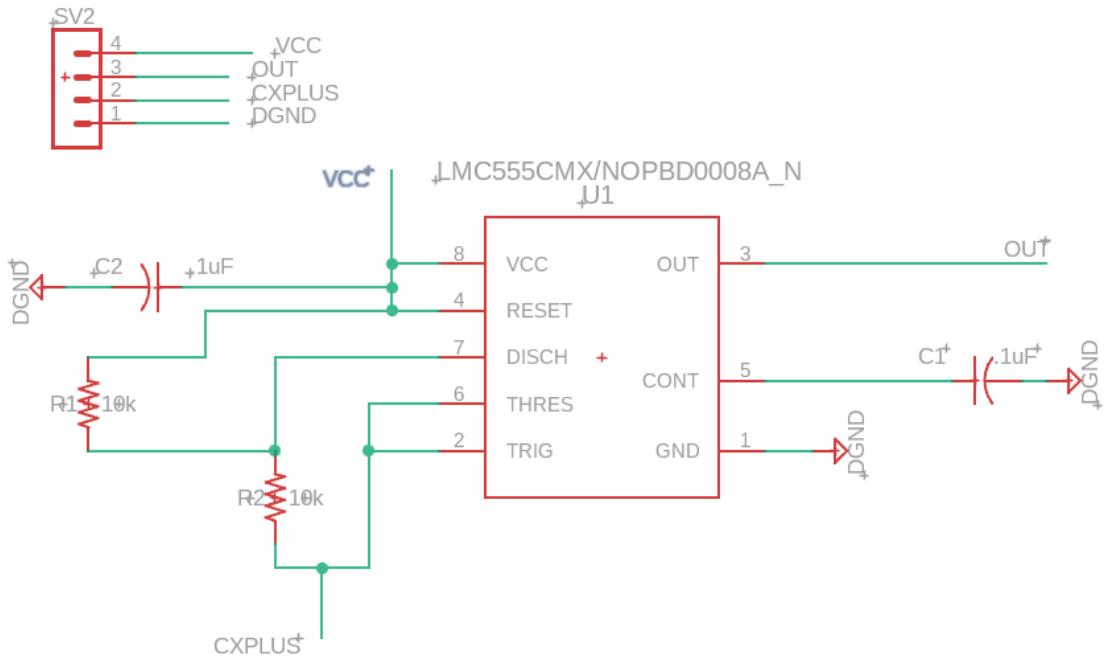


Figure 6.3.1 555 Timer Schematic (created in Fusion 360 by Authors)

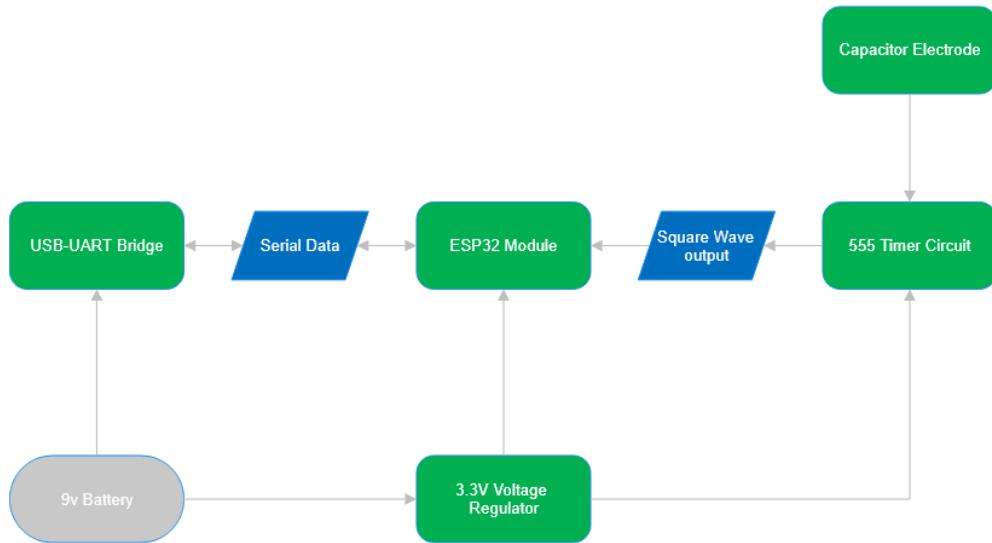


Fig 6.3.2 Hardware System Flowchart V3

CHAPTER 7 - SOFTWARE DESIGN

7.1 Introduction

The software design for the EASE Notifying Feminine Hygiene Pad was responsible for facilitating real-time data collection, transmission, and a notification system. By integrating advanced Bluetooth Low Energy (BLE) communication protocols, the system enabled secure and reliable data transmission from the device to the user's mobile application.

The software architecture consists of three main components:

1. The MCU BLE Transmission Code: This component handles the initialization and configuration of Bluetooth Low Energy communication protocols on the microcontroller unit (MCU), manages connections, and transmits sensor data.
2. BLE Configuration Code: Focused on defining the Bluetooth Low Energy services and characteristics, this component relates to the app code and how it handles the MCU transmission.
3. Sensor Code: This component handles the code responsible for calculating threshold levels and rechecking levels on a polling basis. When the desired threshold is met, then the transmission notification will begin.

The goal of the software design was to create a user-friendly, energy efficient, and reliable system that addresses the core needs of the EASE project. By leveraging modern BLE technology built into the MCU, the system will provide an integrated, robust solution for real-time monitoring of fluid volume in the feminine hygiene product, helping the user manage their menstrual cycle with greater ease and confidence.

This chapter defines the design, its implementation, and how these components were tested. The discussion includes charts, data structures, algorithms used, and considerations taken while writing any software for the Ease Notifying Feminine Hygiene Pad project.

7.2 System Overview

The following sections provide a system overview of the software design, depicted in various diagrams.

7.2.1 Use Case Diagram

The use case diagram for the feminine hygiene product project highlights the interactions between the system and its users, focusing on key functionalities for monitoring and alerting to prevent any potential leaks. The primary actor, the User, engages with several core use cases, including wearing the pad, monitoring fluid levels, and receiving notifications if a leak is detected. The system uses sensors to continuously assess fluid saturation and alerts the user when the risk of leaking is high, through a Bluetooth-connected mobile app.

7.2.2 Activity Diagram

The process begins with the system initialization, where the device checks the battery and sensor status to ensure they are functioning correctly. Once initialized, the system continuously monitors fluid levels in the pad.

At the core of the diagram is a decision point where the system evaluates if the fluid level is below a pre-set threshold. If it is, the system continues monitoring. If the threshold is exceeded, the system triggers an alert to notify the user of a potential leak risk. The user acknowledges this notification, which ends the monitoring phase.

After the notification, the product moves to the end of use phase, where the device is either reset for another cycle or ready for necessary maintenance like battery replacement.

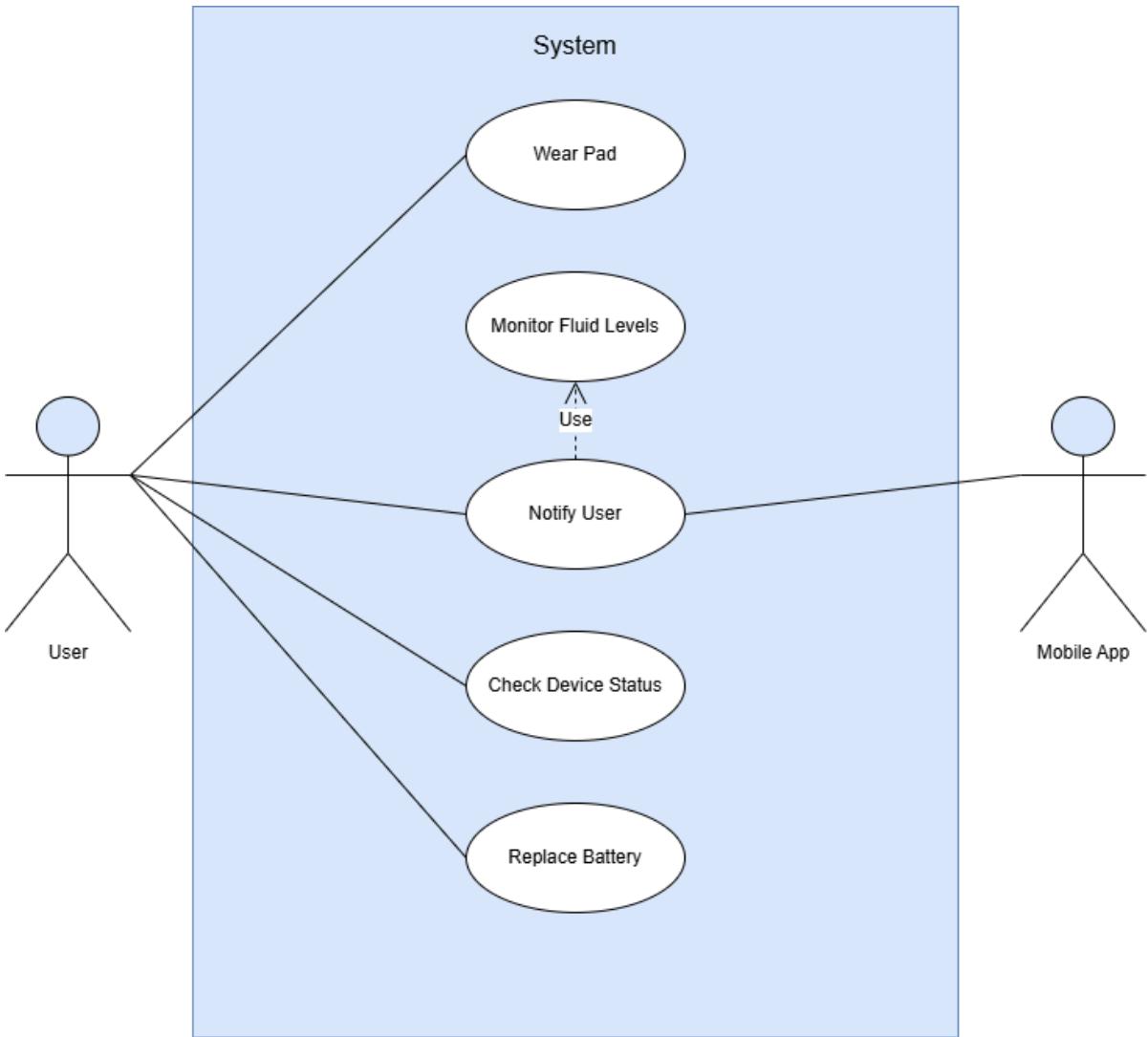


Figure 7.2.1.1 Use Case Diagram for the device (Created in Draw.io by the Authors)

7.3 BLE Code on MCU

The Bluetooth Low Energy (BLE) code on the MCU is responsible for handling all Bluetooth Low Energy communication between the sensor-equipped pcb and a mobile application. This includes initializing the BLE stack, establishing secure connections, and transmitting sensor data to the mobile app when the fluid volume threshold is reached.

The BLE peripheral device, or MCU in our case, advertises itself to allow a mobile application or other BLE scanners to discover it. Advertising includes broadcasting device information such as device name, UUIDs of supported fluid volume services, and signal strength for connection prioritization (RSSI). The code ensures that it is handling BLE security features such as bonding, which saves the pairing information for future connections, and encryption to ensure data confidentiality during transmission. The code

should send a transmission when the sensor detects a fluid level of 90% or greater, in which case the MCU will write the fluid volume data and send a notification to notify the user.

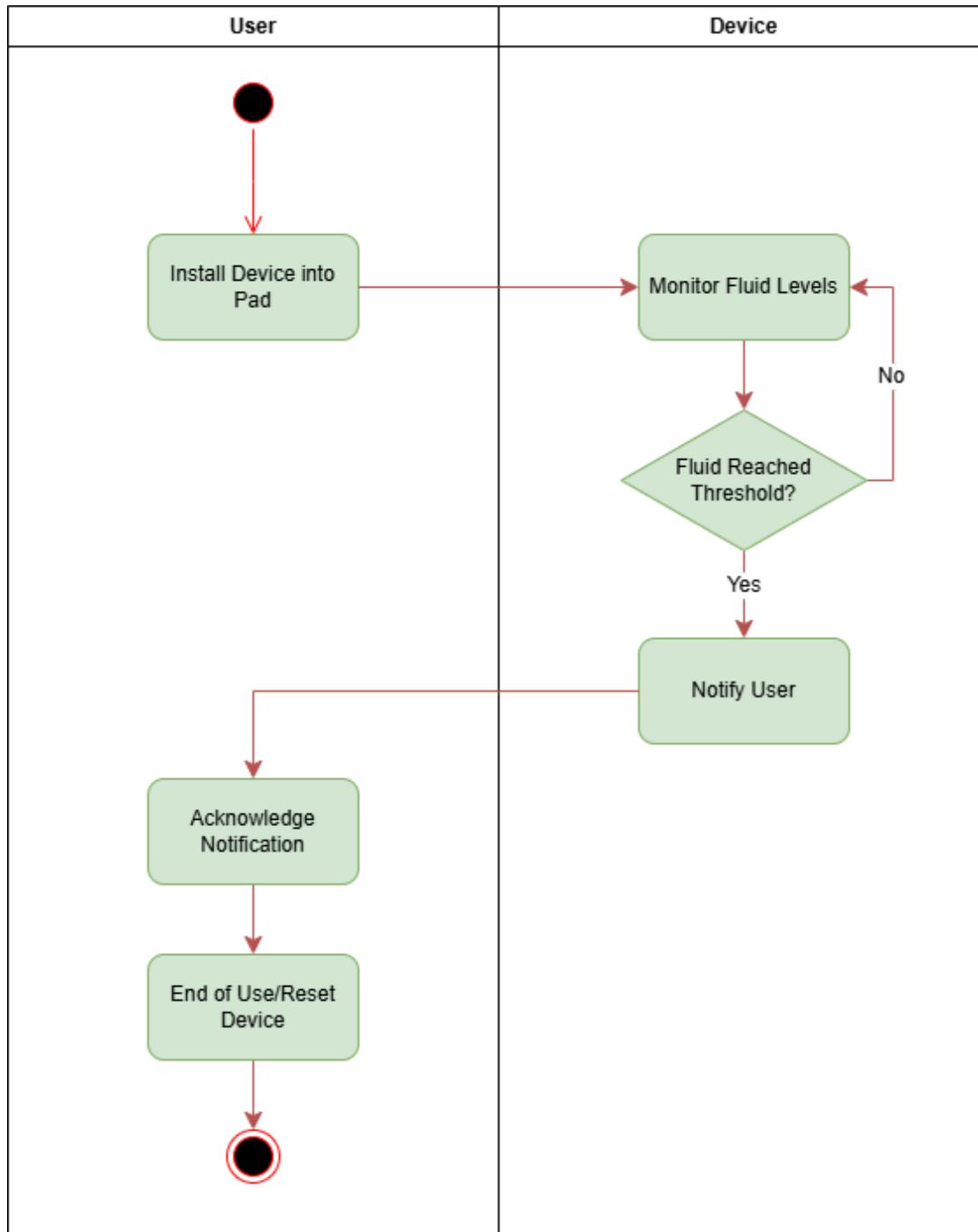


Figure 7.2.2.1 Activity Diagram for the Device (Created in Draw.io by the Authors)

7.3.1 Implementation

In order to implement the Bluetooth Low Energy (BLE) code on the MCU, we utilized the BLE stack provided by Arduino for the ESP32 MCU. Using Arduino's stack ensured energy efficiency, as it was optimized for low-power devices like the ESP32, and it reduced memory usage by integrating directly with the application task. Although we initially considered using TI's Micro BLE Stack for its GATT service support, we proceeded with Arduino's stack, which still allowed us to define custom GATT services—specifically for fluid volume and threshold status.

The BLE stack was configured to handle key events, including advertising, connection establishment, and data writing. When powered on, the device began advertising and broadcasting, and stopped advertising once a connection was established to conserve power. The stack monitored connection events such as disconnections and successful pairings. It also wrote sensor data to a BLE characteristic and notified the connected device whenever characteristic values changed.

BLE Implementation Steps:

Step 1: Configuring the BLE Stack

- We configured the BLE stack by loading the provided Arduino code into the ESP32. The BLE role was defined as a server with multi-connect capability. Advertising intervals were set to balance power consumption with discovery latency.

Step 2: Defining BLE Services and Characteristics

- We defined custom BLE services and characteristics. The service included characteristics for Threshold Status. Threshold Status was stored as a string containing certain key phrases.

Step 3: Initializing BLE Advertising

- We initialized BLE advertising by setting parameters such as device name and advertising interval using the Arduino BLE API.

Step 4: Establishing Connections

- We handled connection events within a BLE callback function, including restarting advertising after a disconnection and initiating the notification service upon successful connection.

Step 5: Writing and Notifying Data

- We implemented a function to update the Fluid Volume characteristic with the latest sensor readings. Additionally, we created a function to send a notification to the connected mobile app when the fluid level breached a threshold. This ensured the mobile app received real-time updates from the sensor.

7.3.2 Flowchart: BLE Connection and Data Transmission

The following flowchart for BLE Connection and Data Transmission shows the sequence of events for the initial BLE communication and data transmission. The sequence begins with the BLE stack initialization. As soon as the BLE stack is initialized it can begin advertising its broadcast to nearby devices. Once a device discovers and attempts to pair with the MCU, it will send a pairing request. The pairing request will then follow a password verification system and if successful the connection will be established, else another pairing request must be sent. Once the connection is established, the sensor will begin its polling. If the sensor calculates and detects that the fluid level has reached the 90% threshold, the mobile app will be notified, once again via BLE communication. If the sensor code does not detect the threshold being met, it will continue the polling cycle until detection is reached. Once the notification is sent to the device it will monitor the connection made. If the connection is lost, it will restart the connection by re-advertising, requiring a new pairing. If the connection is not lost, the code will terminate after its procedures have resolved.

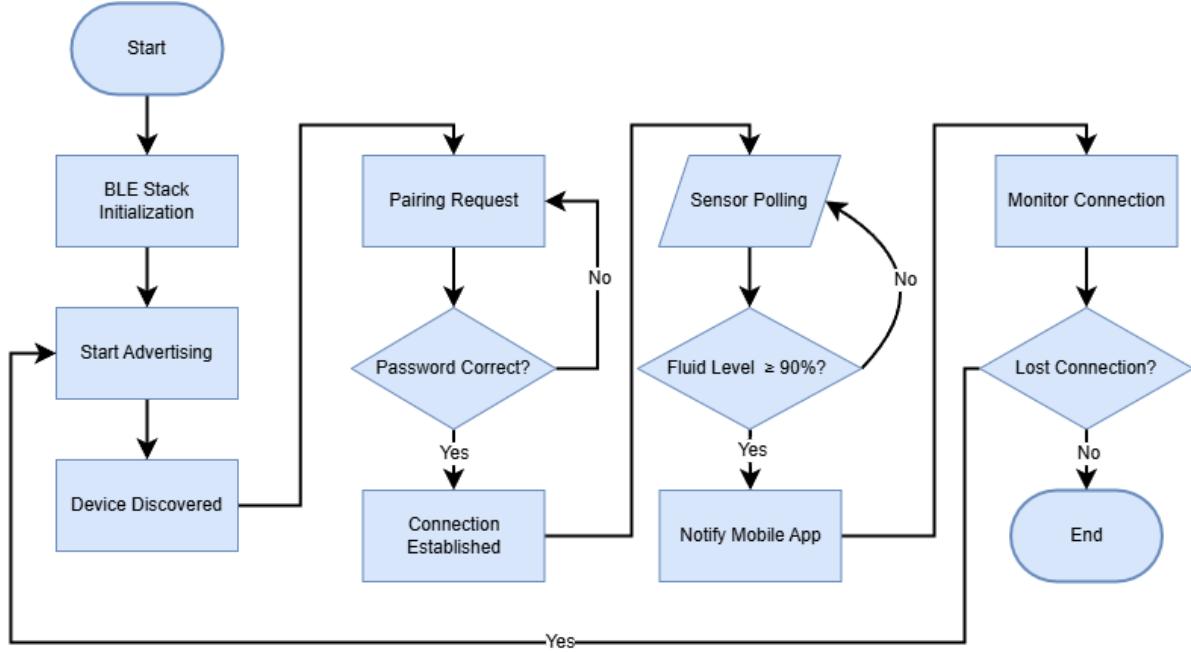


Figure 7.3.2.1 Flowchart Showing BLE Connection and Data Transmission (Created by Authors in Draw.io)

7.4 BLE Configuration Code

The Bluetooth Low Energy (BLE) configuration code defines how the system organizes, formats, and exchanges data over BLE. It establishes a custom Generic Attribute Profile (GATT) service to communicate fluid volume data and device status securely between the MCU and a connected mobile device.

A few key features were required to be covered by this code, one being the custom GATT service group for fluid monitoring. The service focuses on sending fluid volume percentage and indicating whether or not the three threshold has been exceeded. The data exchange includes a string message for the type of fluid threshold that has been exceeded.

7.4.1 Implementation

In order to configure the Bluetooth Low Energy code from the MCU to the mobile application, we needed to set up two types of UUIDs.

Steps for BLE Configuration:

Step 1: UUIDs for Service and Characteristics

- Service UUID for the fluid monitoring service and characteristic UUID for such as threshold message.

Step 2: Permissions

- We also needed to set up the proper permissions and define access levels for characteristics. We needed to set up read, write, and notify permissions. Read permissions allows the mobile app to fetch data. Write permissions allows the mobile app to update configuration settings and trigger actions. Notify permissions pushes data to the mobile app whenever the characteristic value changes.
- The UUIDs were set, as well as their properties which include read and notify for fluid volume and read and write for status. Then the permissions were also defined in the two variable definitions, with the fluid volume having a read permission and the status having a read and write permission.

Step 3: Service and Characteristic Registration

- The service and characteristics must be registered with the Bluetooth Low Energy (BLE) stack during initialization which can look like a custom variable set with a UUID and characteristics of fluid volume and status. That custom variable would then be passed to a register function to handle the registration.

Step 4: Event Handling for Data Updates

- BLE stack event handlers monitor for client requests such as read and write and trigger the corresponding actions. We created an event handler for reading call back and another event handler for writing call back. The read call back function has a conditional to check if the UUID matches fluid volume and if so, it returns the current fluid volume, but if the UUID matches that of status, it returns the system's status. The write call back will check if the UUID matches that of status and updates the system status if the match is found.

Step 5: Notification Mechanism

- When the sensor detects a threshold breach greater than or equal to 75% or 95%, the system triggers a notification. This is handled with a global variable for predefined thresholds and simple conditionals that lead to a function that handles the notification.

7.4.2 Flowchart: BLE Configuration

The following flowchart for BLE Configuration shows the sequence of events for the configuration side and mobile side of the BLE connection. The sequence begins with the BLE service being initialized. The BLE service is created and configured using the provided BLE from Arduino. Once the BLE service is up and running it must advertise and establish a connection with a mobile device. The mobile device must be ready to receive the transmissions from the MCU in order for a data exchange. The data exchange can occur either via initiation from the client side or the server side (this being the code for the sensor or MCU). Once a successful data exchange is met the sequence has completed its goal. The data exchange step is repeated until the notifications are set and the MCU stops the connection.

7.5 Sensor Code

The sensor code handled the interaction with the fluid volume sensor by processing raw data to determine whether the 75% threshold or 95% threshold had been met. Upon detecting that the threshold was reached, it triggered the BLE notification process to alert the user. Several key features were considered in the sensor code, including the sensor configuration protocol and the sensor's operating parameters, including polling rate and sensitivity.

The goal of the configuration code was to ensure the sensor operated within its specified range to provide accurate readings. The sensor code reads data from the sensor at regular intervals using polling, implemented with a timer to minimize power consumption during idle periods. It also compared the current fluid volume to a pre-established threshold by processing the raw sensor data, calculating the fluid volume as a percentage, and evaluating whether it exceeded the predefined threshold value.

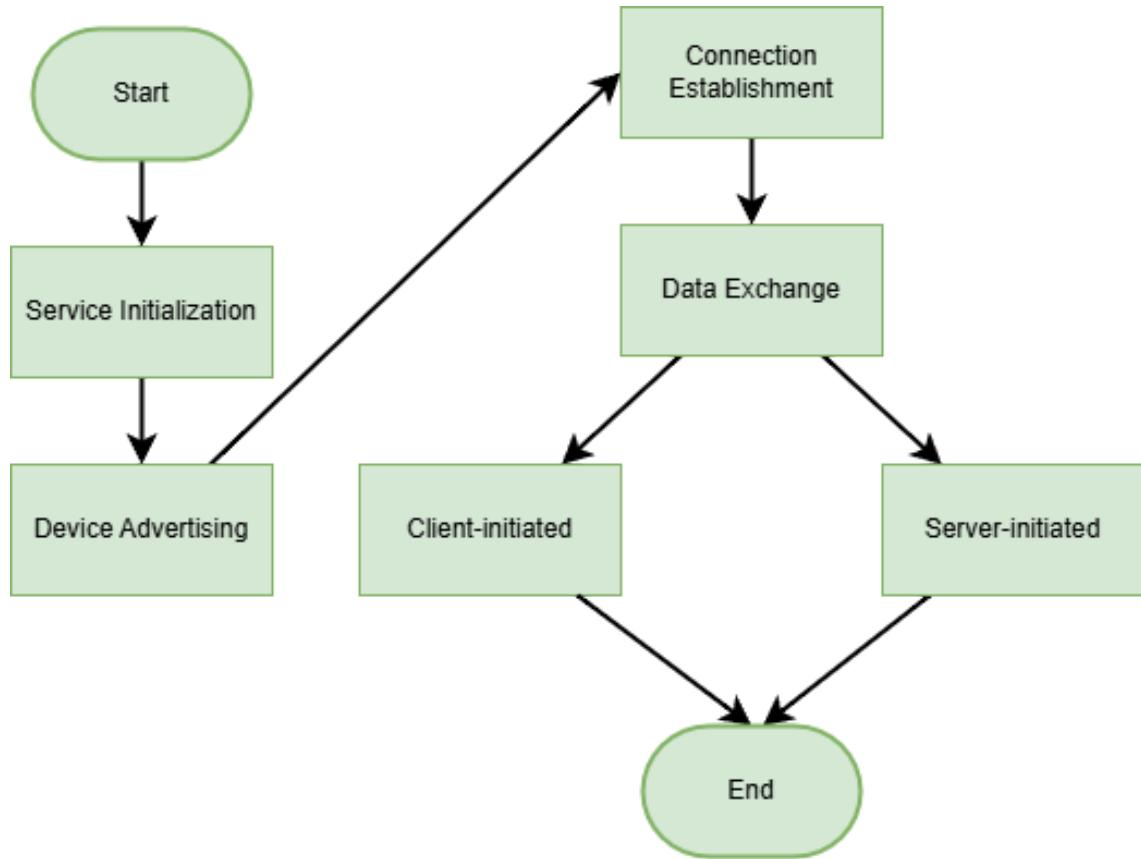


Figure 7.4.2.1 Flowchart Showing BLE Configuration Process (Created by Authors in Draw.io)

7.5.1 Implementation

In order to configure the sensor code we needed to follow a few steps for implementation.

Steps for Sensor Code:

Step 1: Sensor Configuration

- The sensor configuration entailed setting the sensor to its correct communication type. Arduino datasheets, user guides, and the Arduino IDE provided extensive resources to assist with this configuration. Once the correct communication type was initialized, we configured the sensor's specific registers and values, and assigned the necessary permissions for operation.

Step 2: Periodic Polling

- We used a timer interrupt to implement a low-power polling loop, allowing the system to conserve power efficiently. The program remained in low-power mode

and periodically woke up to poll the sensor. During each polling cycle, the sensor data was processed and compared against a predefined threshold value.

Step 3: Data Processing and Threshold Checking

- To process the data, we created a function that normalized the raw sensor readings into a percentage, returning the value as an unsigned 8-bit integer. If the returned value exceeded the set threshold, the notification function was triggered to alert the user to change their hygiene pad.

Step 4: Error Handling

- The sensor code included mechanisms for error handling, addressing edge cases such as sensor disconnects, out-of-range values, and communication failures. When an error condition was detected, it was logged appropriately, and the system attempted to reset the sensor and resume normal operation.

Step 5: Low-Power Modes

- We utilized the low-power modes available through the Arduino IDE. The system was configured to sleep between polling intervals and to disable unused peripherals during idle times to maximize power efficiency.

7.5.2 Flowchart: Sensor Code

The following flowchart for the sensor code illustrated the sequence of events the sensor underwent after being powered on. As soon as the sensor was activated, it entered low-power mode and began polling at predefined intervals. These intervals were chosen to balance energy conservation with reliable BLE communication.

During each polling event—or upon an interrupt—the sensor woke up and captured the latest fluid volume data. This data was then processed into a percentage. If the total percentage was below 75%, the sensor continued its polling cycle. If the total percentage was greater than or equal to 75% and then 95%, the sensor stopped polling and triggered the notification function.

This notification function sent the necessary information to the mobile device, which then informed the user that their hygiene product had reached capacity and needed replacement. After sending the notification, the sensor returned to low-power mode to continue its monitoring cycle.

In the event that the sensor or code encountered an error during startup or operation, the issue was logged, and the system attempted to reset and retry the proper sequence of operations.

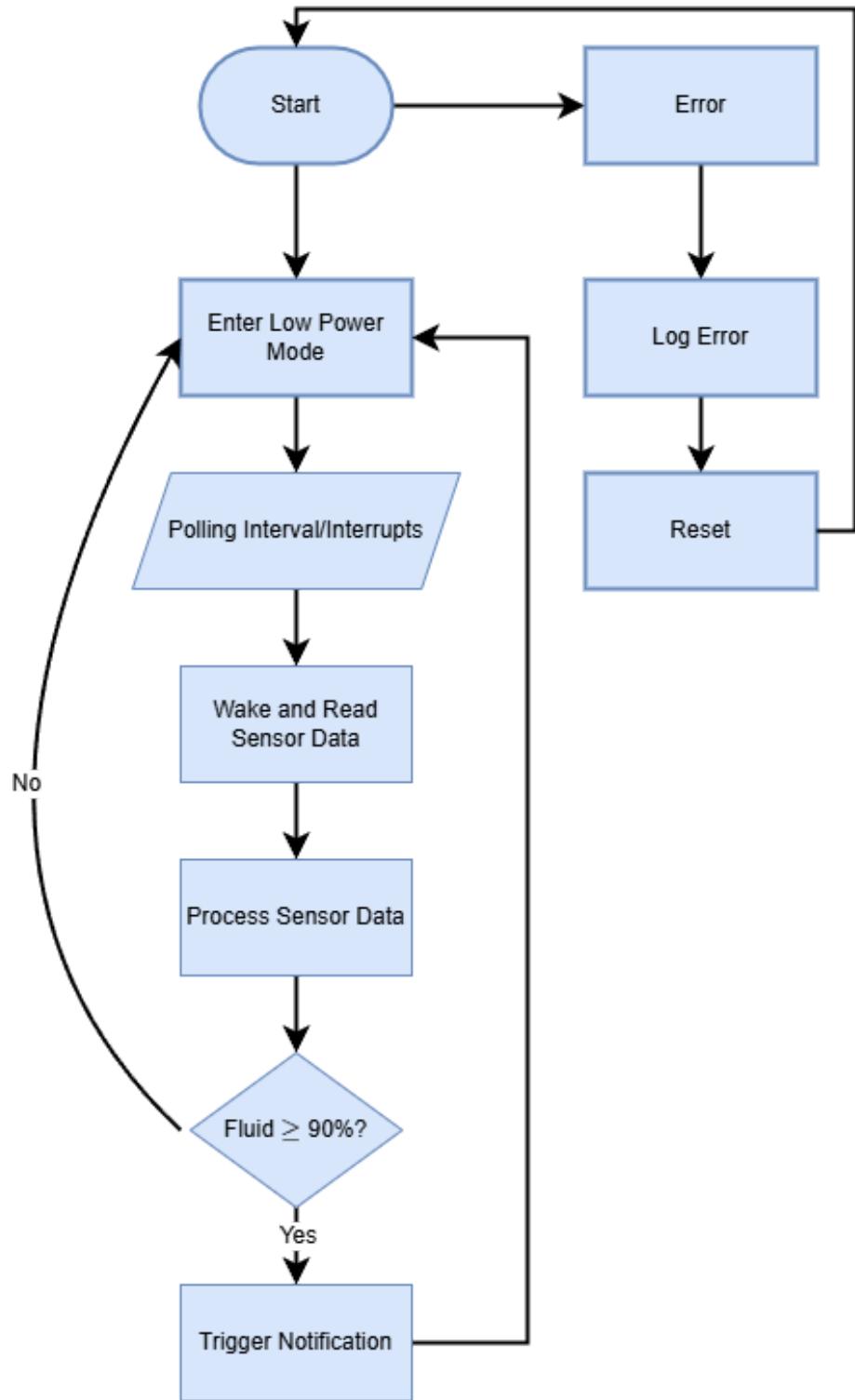


Figure 7.5.2.1 Flowchart showing how the sensor code will work (created by the Authors using Draw.io)

7.6 Challenges and Future Enhancements

The software design had its own challenges and potential future improvements, which were considered as design choices were finalized. We first addressed the challenges, as they pertained to the current implementation and the obstacles we needed to overcome to achieve our software goals.

One major challenge was ensuring that BLE connectivity functioned reliably in noisy environments. Interference from other wireless devices operating in the same frequency band—such as Wi-Fi or other BLE devices—sometimes affected communication reliability. To address this, we optimized the advertising and connection intervals to minimize packet collisions and retries.

Another challenge was maintaining battery life. Continuous polling for sensor data and BLE operations placed a strain on battery resources, so we implemented power-saving techniques such as low-power modes and efficient polling intervals.

Managing compatibility across mobile devices was also an important consideration. We tested the system on a variety of devices, including both Android and iOS platforms, and adjusted configurations as needed to ensure proper functionality and compatibility.

Future possibilities for the software design included implementing extended BLE range features such as BLE long-range mode, and integrating AI to analyze fluid data trends, predict usage patterns, and provide personalized recommendations for hygiene product changes or alerts.

CHAPTER 8 - SYSTEM FABRICATION

System fabrication is a key phase in the development of a prototype, where conceptual designs and schematics are transformed into a physical, working model. This stage involves assembling components, integrating hardware and software, and ensuring that all parts of the system function together as intended. Effective fabrication allows designers to test their ideas in real-world conditions, identify flaws, and make necessary improvements. It also provides valuable insight into manufacturing feasibility, material selection, and overall system performance. Ultimately, system fabrication bridges the gap between theory and practice, playing a crucial role in bringing a prototype to life.

8.1 PCB Layout

PCB design and placement of components was done in the Autodesk Fusion 360 software application. For the main PCB, automatic routing was performed within Fusion 360. Adjustments were then made to the PCB design to conform to the hardware configuration requirements and PCB design considerations of the MCU specified within the datasheet [\[Data-4\]](#). Certain requirements such as oscillator load capacitors were to be placed

symmetrically with short connections to ground in order to reduce electro-magnetic interference (EMI). Tented vias were used under ground pads for the mcu and battery holder to ensure more protection and it may become necessary to tent all vias on the pcb. Minimal usage of traces on the bottom layer and short traces on the bottom layer were used to keep a more contiguous ground plane and provide shorter current return paths. This is important especially for RF PCBs where EMI can greatly impact the quality of the signal. Extra space was incorporated at the top and bottom to provide space for adhesives for application to the feminine hygiene pad. For the sensor pad PCB, exclusion polygons were utilized to ensure that routing did not cross over copper pads. The following figures present the initial PCB design for both the main PCB and sensor pad PCB as completed in the Fusion 360 application. Modifications and adjustments to these initial designs will likely be necessary as construction and development of an initial prototype begins.

8.1.1 Hardware Layout V1

The following figures present the PCB layouts for the initial design, adhering to the design rules previously mentioned. Circuits were placed in such a way to maximize compactness of the design. The electrode pad places the capacitive sensor in the center, with the solid state sensors along the perimeter to detect leakage.

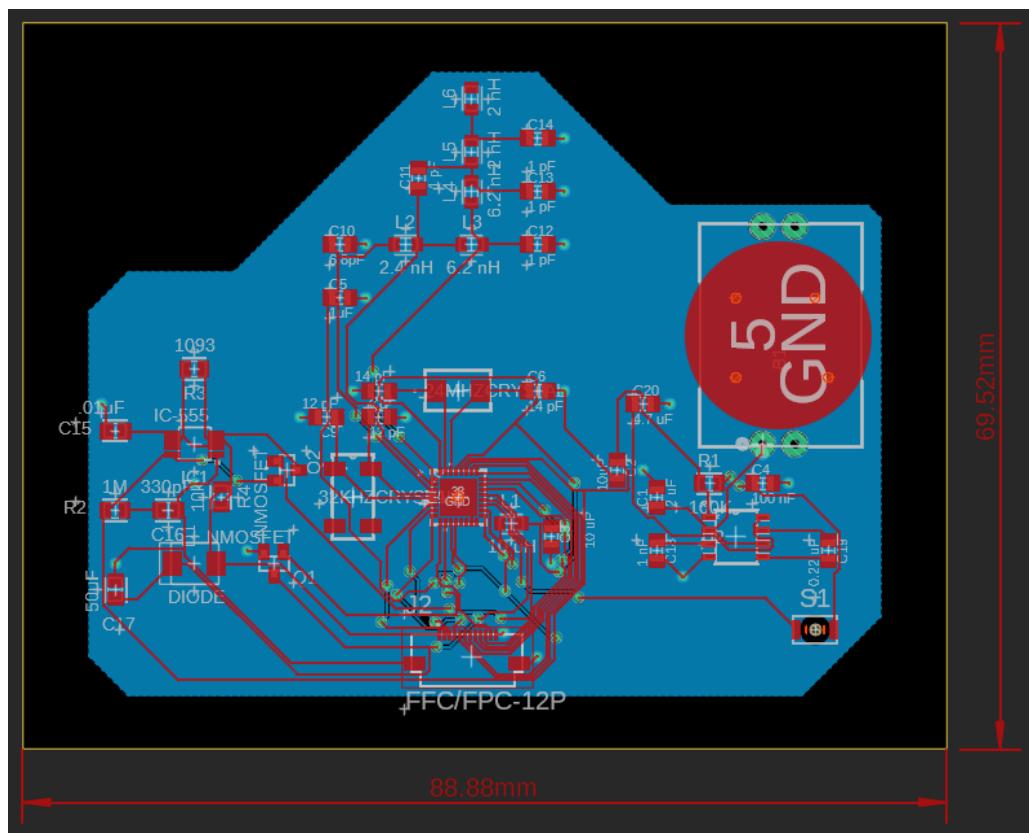


Figure 8.1.1.1 Main PCB V1 (produced in Fusion 360 by Authors)



Figure 8.1.1.2 Electrode Pad PCB V1 (produced in Fusion 360 by Authors)

8.1.2 Hardware Layout V2

The second iteration of the hardware layout was made to incorporate the ESP32-WROOM, USB to UART, and Capacitance to Digital Converter extension circuit schematics previously mentioned in Chapter 6. Circuits were placed to closely adhere to the recommendations as provided by the respective datasheets.

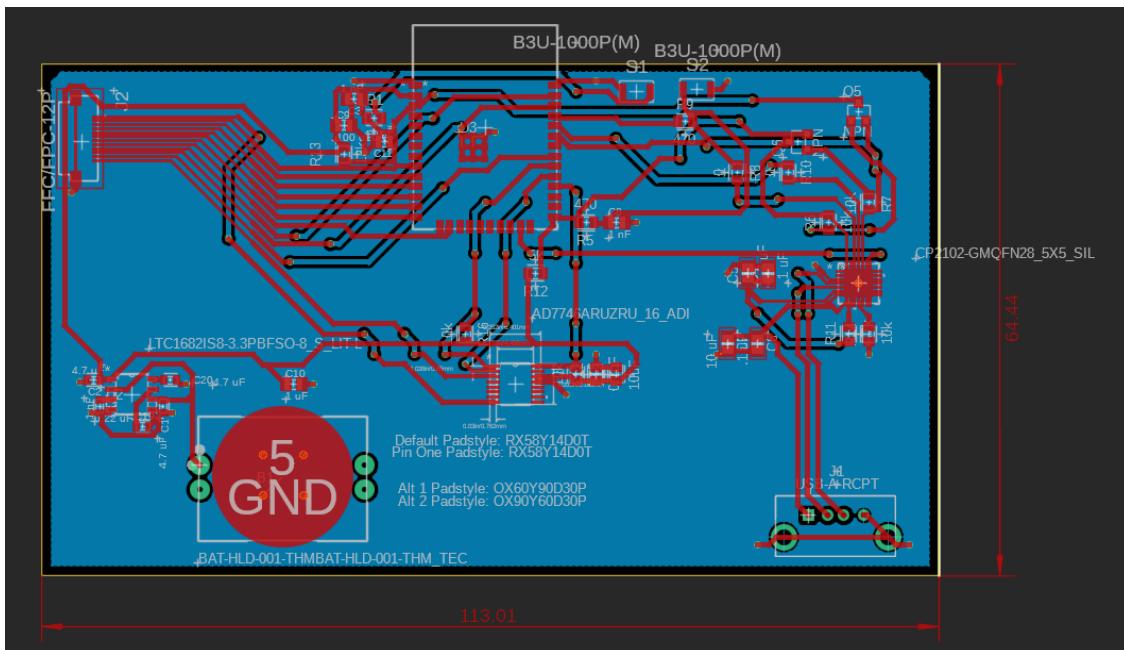


Figure 8.1.2.1 Main PCB V2 (produced in Fusion 360 by Authors)

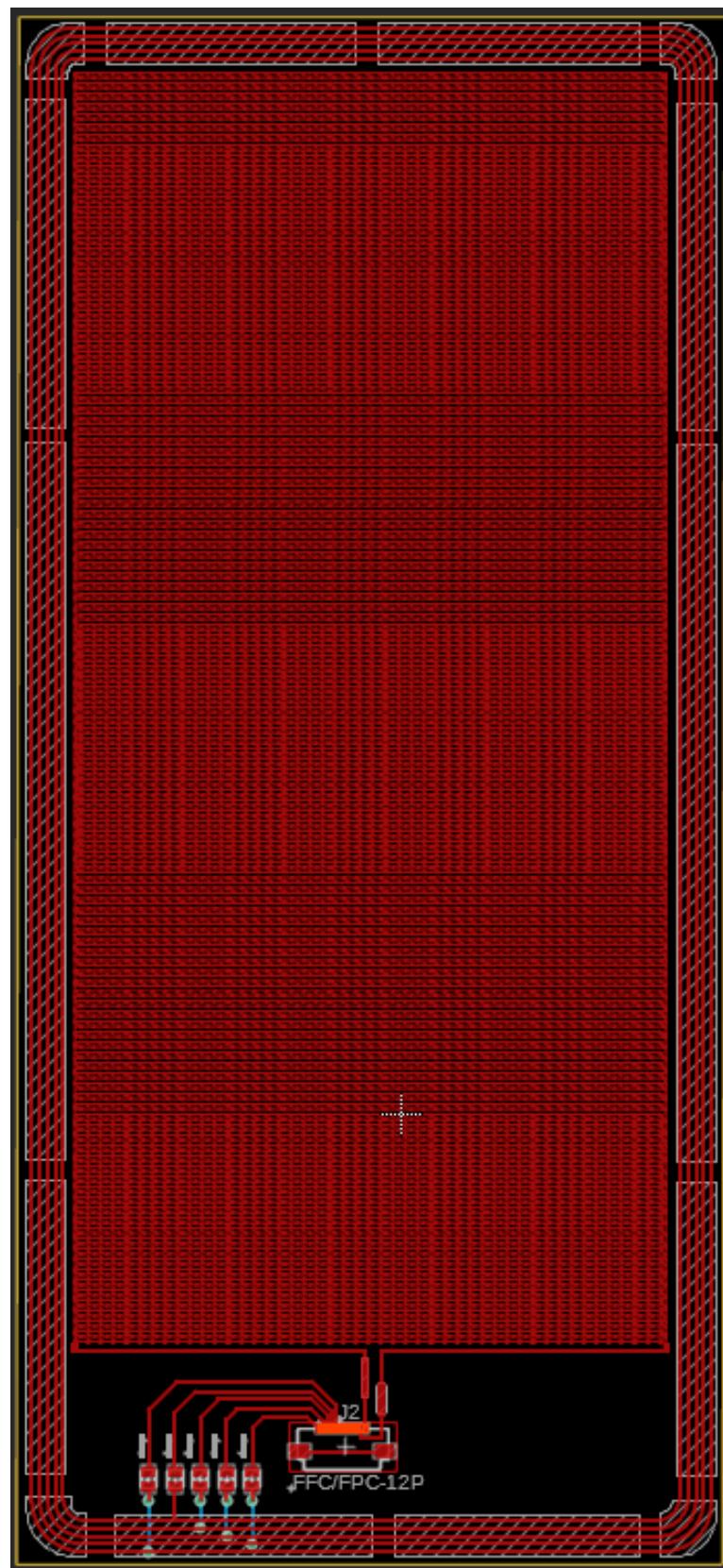


Figure 8.1.2.2 Electrode PCB V2 (produced in Fusion 360 by Authors)

Additionally, the electrode pad was re-designed to minimize component use on the FPC, as well as maximizing effectiveness of the capacitive electrode. The solid state arrays were removed and replaced with concentric rings. These would remain exposed to act similarly to the previous design. However, a short across any pair of rings would indicate that lateral leakage is about to occur. The capacitive sensor was re-designed to maximize the full space of the FPC. The interdigitated design allows for higher capacitive precision with greater surface area coverage. This new design virtually removes any components, with the exception of four resistors and the ribbon cable connector, allowing it to be fully integrated with a feminine hygiene pad with virtually no electronics as preferred by the user.

8.1.3 Hardware Layout V3

Due to time constraints, re-ordering another main PCB to accommodate the 555 Timer instead of the CDC circuit was inappropriate. Instead, the 555 Timer circuit was designed on a breakout board that was then directly applied to the Main PCB V2. Traces were exposed to directly wire the output of the 555 Timer to the corresponding ESP32-WROOM pin. Additionally, the NCP1117 voltage regulator was directly applied to the main PCB. Jumper wires were then used to establish the corresponding connections so that each subsystem was properly powered and interconnected.

8.2 Theoretical Product Integration

Each of the hardware components utilized for this project must be seamlessly integrated with a feminine hygiene pad. The physical and environmental constraints previously stated require that our design be of minimal size and weight so that the device itself feels virtually indistinguishable from the hygiene pad itself. Additionally, the electronic hardware must be resistant to bodily fluids and dust particles to ensure continuous use and reliability when used. The following sections describe the integration requirements for each primary piece of hardware for the device and how it will be designed to be integrated with a hygiene pad for prototyping.

8.2.1 Main PCB Integration

In order to maximize the physical protection of a flexible PCB without adding unnecessary bulk or weight that will hinder the flex properties of the PCB, a silicone conformal coating will be applied to the main PCB. Silicone conformal coating will protect the PCB from wide temperature ranges produced from body temperature, moisture and humidity from bodily fluids, dirt and dust contaminants from contact with clothing or the pad itself, and vibrational stresses due to movement while maintaining physical flexibility.

The main PCB will then be attached to the bottom side of the hygiene pad via medical grade silicone adhesives, effectively acting as tape. In real application, the user must

attach and detach the device to the hygiene pads themselves for repeated uses. Utilizing medical grade adhesives provides quick and easy application that can be conveniently removed and reapplied for re-use. Additionally, it provides the user the ability to precisely place the PCB themselves based on individual preference. Application of the main PCB to a feminine hygiene pad is shown in the following figure.

Another aspect that needs to be considered is the inclusion of an antenna. As part of the demonstration video, an antenna is built in with the MCU development board being used. However, the MCU component will likely require an antenna to be integrated with it within the main PCB based on its associated data sheet and reference schematics. Integration of this additional component must further be considered when prototyping the main PCB into the full design.

8.2.1.1 Hardware Considerations

Due to the small nature of our project there needs to be considerable design considerations when creating the PCB that would not normally need to be considered. We are lucky to be using Bluetooth as it operates in the 2.4 GHz band meaning our antenna does not need to considerably increase the footprint of our main PCB but having a PCB antenna does mean we will need to be careful in its placement relative to the ground plane and surrounding SMD devices.

[Data-4] Lists some measures TI advises designers to take when implementing a PCB antenna and [Data-6] lists some of TI's own PCB antenna designs that can be selected. One of these antennas has already been tested as it is used on the Launchpad we used to test which will be further explained in chapter 9. Besides just the antenna considerations there are also other considerations that need to be taken into account from [Data-4]. As discussed in the 8.1 PCB layout chapter, symmetrical load capacitor setups for the crystal oscillators is important.

What was also taken into consideration when designing the PCB was the relative distances between the transmission circuit and the MCU and the MCU's internal DC-DC converter and its connection to ground. The ground plane was kept solid under the MCU with extra space for the DC-DC pins to have adequate unbroken access to the ground plane to ensure a quality DC supply. This was done in Fusion 360 by using the restricted bottom layer. A polygon shape can be created on this layer removing access to traces and pours which allows the auto router to run without interrupting the ground pour layer below. This polygon can then be removed after filling in the ground layer. This technique was used more in the electrode pad PCB which will be discussed later.

8.2.2 Sensor Pad PCB Integration

Integration of the sensor pad PCB presents a challenge, as it contains both capacitive and solid state electrodes which have different integration requirements for proper functionality. The primary difference is exposure, as the capacitive electrodes must be covered in a film while the solid state sensors must be exposed.

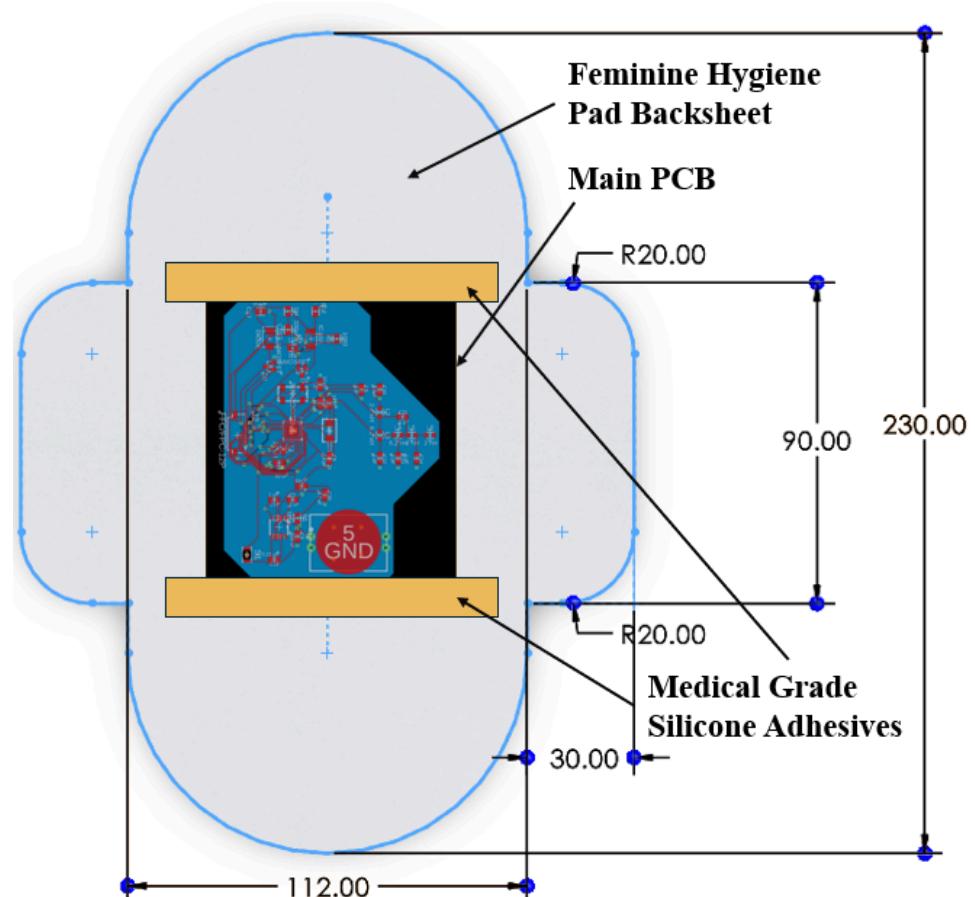


Figure 8.2.1.1 Main PCB Integration (produced in SOLIDWORKS by Authors)

The film for the capacitive sensors serves a multitude of purposes, providing protection from the environmental demands, improving sensor sensitivity and functionality by acting as a dielectric layer and reducing noise, and increasing the durability and longevity of the sensor itself. However, this same film will act as a hindrance to solid state sensors which are designed to work in direct contact with the fluid it is expected to detect. Due to the physical requirements of each respective electrode being used, two implementation options exist.

8.2.2.1 Single Sensor PCB Implementation

The first option combines both the capacitive electrodes and solid state electrodes being used onto a single PCB to consolidate space and minimize complexity. To create the film required for the capacitive electrode, silicone conformal coating can be selectively applied to the sensor pad PCB so that only the solid state sensors remain exposed. Similar to the main PCB, the silicone conformal coating will act as a protective coating for the main body of the PCB while simultaneously creating a film for the capacitive electrodes.

Once coated, the PCB must be placed beneath the very top layer of the hygiene pad to allow the solid state electrodes to detect leakage along the perimeter and the capacitive

sensor to detect hygiene pad capacity. This placement allows for optimal sensor functionality while also minimizing direct bodily contact with the device which may create false triggers. Since the PCB would be directly integrated between the layers of the feminine hygiene product, additional adhesives should not be necessary. The sensor pad PCB will be connected to the main PCB via 12 PIN FPC FFC flexible ribbon cable as shown below in figure 8.2.2.1.1.

When designing this PCB in Fusion 360 there are some important things to note, the ground layer that is normally used in most applications cannot be used here because of the capacitive sensor, adding a ground layer here would interfere with the properties of the capacitive sensor electrode and give us a field that cannot adequately be affected by a dielectric that is going to be 2-3 mm from its surface. This does not mean that we cannot use the bottom layer for extra routing as the solid state sensors do not share ground connections and will not be active at the same time as the capacitive sensor causing no conflicts.

Another consideration is that the electrode pads need to be designed and placed by hand using the polygon pour function. They act as a switch but we could not find a suitable part to use in the schematic that would correctly transfer over to a pcb. Because of this the nets were instead connected together where the pads would be and the PCB routing was all done by hand to ensure the autorouter would not accidentally route the electrode pads together. In the future when we need to change this PCB design we should look into creating a part that can act as a switch for the schematic and display in the PCB as the electrode pads we have designed.

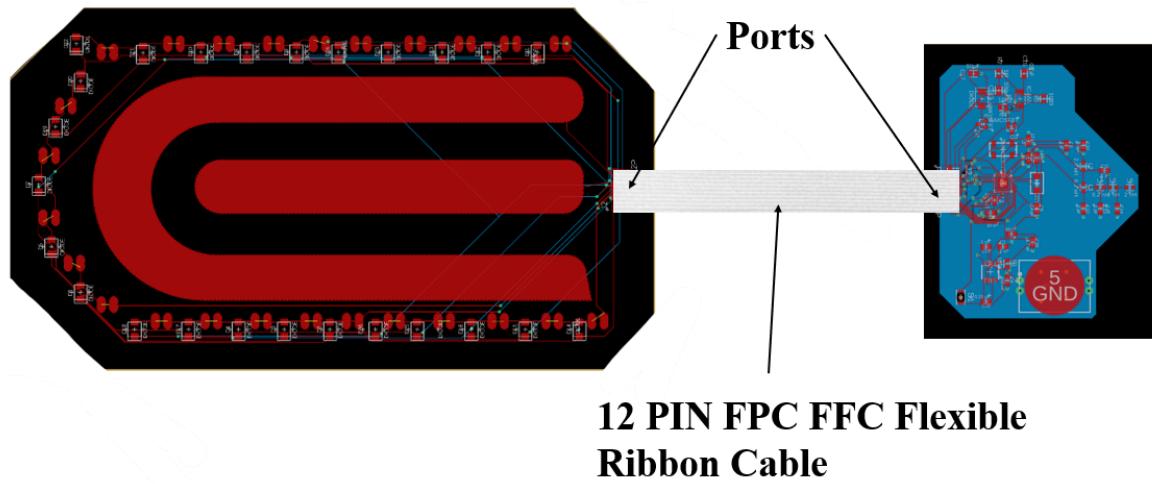


Figure 8.2.2.1.1 Electrode Pad and Main PCB Connection Configuration (produced by Authors)

The following figure provides a visual representation of the consolidated sensor pad PCB's integration with a feminine hygiene pad and its placement below the top sheet.

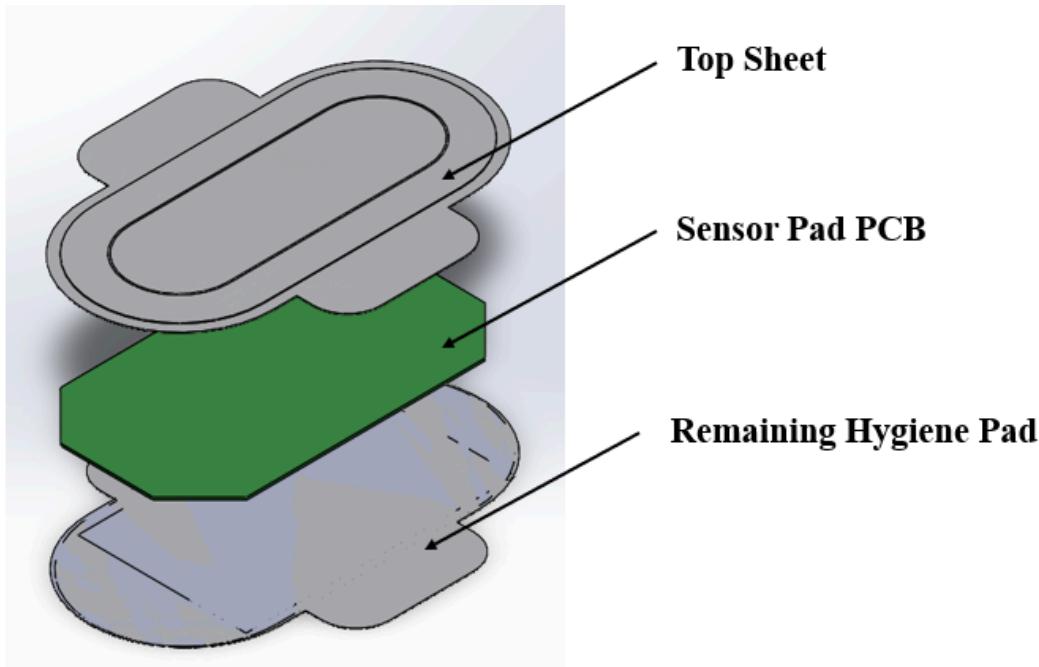


Figure 8.2.2.1.2 Electrode Pad Integration and Placement within Pad (produced in SOLIDWORKS by Authors)

While this option allows us to produce a consolidated design for the sensors with only one PCB, significant issues may arise with the capacitive sensor's functionality. Since the solid state sensors must be below the top layer to directly trigger when in contact with fluid, the capacitive sensor would be forced to sit above the secondary top sheet and absorbent core, which may cause the capacitive sensors to provide inaccurate readings.

8.2.2.2 Breakout Sensor PCB Implementation

To resolve this issue, the sensor PCB can be broken out into two separate PCBs: one to hold the solid state sensors and another one to hold the capacitive sensors. With this implementation, the capacitive PCB can be fully coated in silicone conformal coating while the solid state PCB can remain exposed. Then, the capacitive PCB can be placed between the bottom sheet and absorbent core of the feminine hygiene pad so that it can collect readings accurately from directly underneath the portion of the pad holding fluid. As in the previous implementation, the solid state PCB would be placed between the top sheet and secondary top sheet to directly contact fluid leakage. This implementation is shown in the figure below.

While this implementation resolves the functionality of the sensors being used, a total of three PCBs would be utilized in a singular feminine hygiene pad which may add significant bulk and feel to the overall device, violating the physical constraints previously set. Determining the best implementation will be done during the prototyping phase of Senior Design 2.

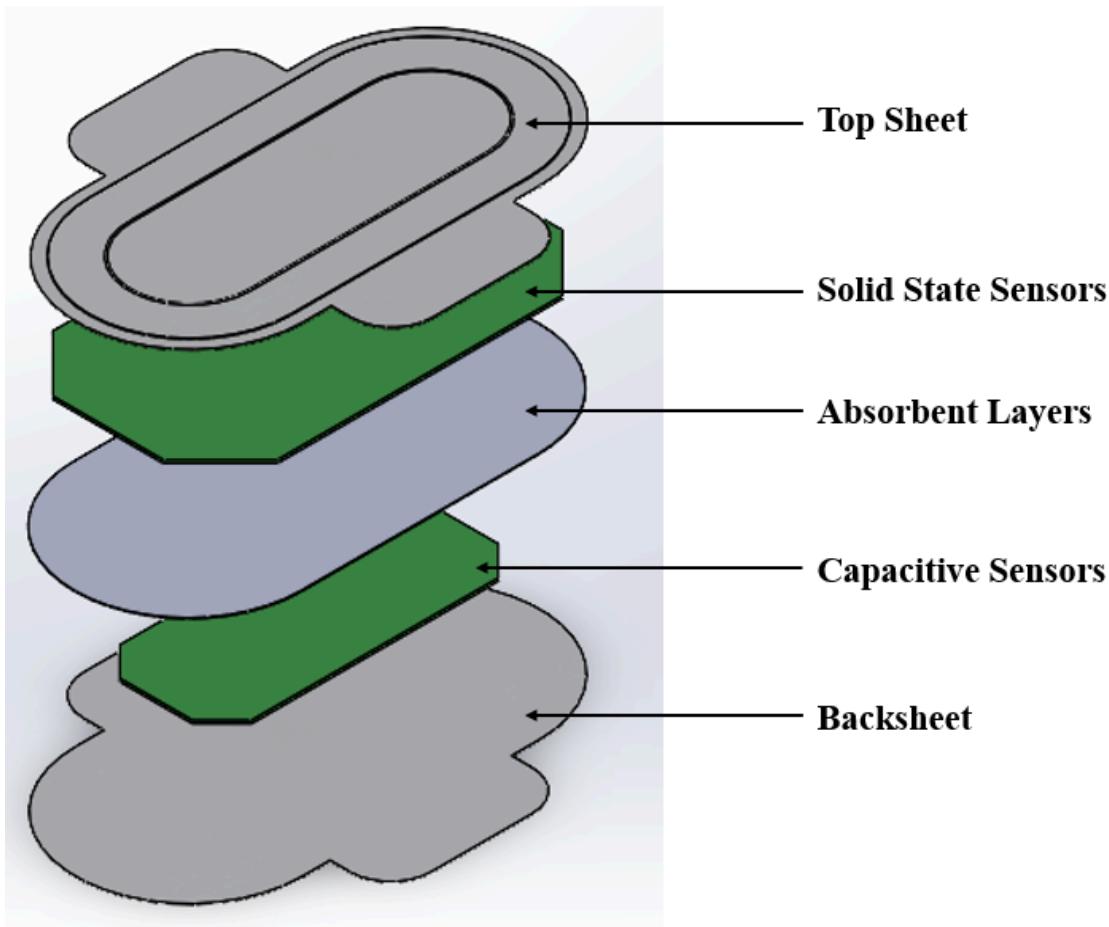


Figure 8.2.2.2.1 Possible Sensor Integration and Placement within Pad (produced in SOLIDWORKS by Authors)

8.3 Theoretical Prototype Layout

Figure 8.3.1 provides a visual representation of the device's complete integration with a feminine hygiene pad and its placement via layers. As previously mentioned, the main PCB and sensor pad PCB will be connected via a ribbon cable to maintain overall compactness and thinness of the overall device.

8.4 Prototype Product Integration

Due to the inherent nature of our design, the main PCB of the prototyped design must be placed externally relative to the feminine hygiene pad, as it is too large and rigid to be integrated within the pad itself. Because of this, the main PCB is placed in an external 3D printed housing unit. As in the theoretical layout, the main PCB is connected to the electrode pad PCB via ribbon cable, with the electrode pad being placed underneath the top sheet. However, it is important to note that the electrode pad is placed above the absorbent pad, rather than below.

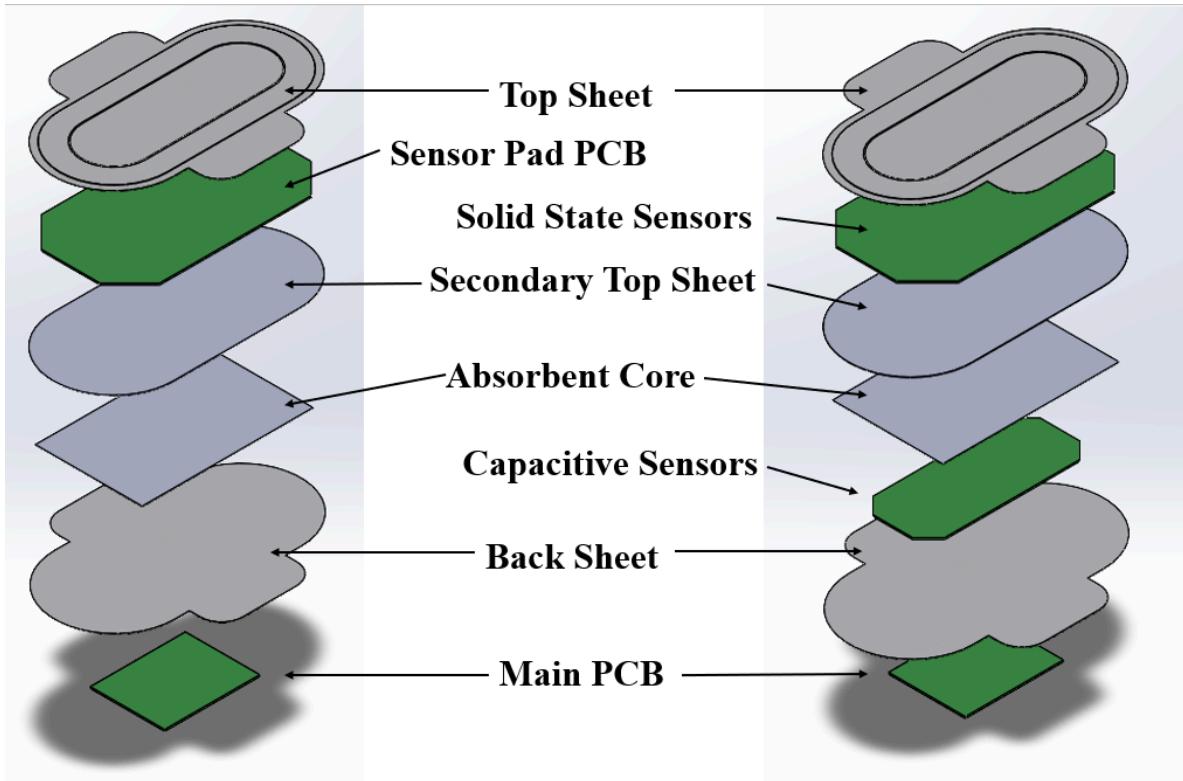


Figure 8.3.1 Full Hardware Integration (produced in SOLIDWORKS by Authors)

This is because the absorbent layer contains a gel agent that thickens and collects as it absorbs fluid. Since practical testing within senior design required quick absorption time, the gel agent caused the absorption rate to vary significantly, negatively impacting measured frequencies. To eliminate such variability, the absorbent pad was effectively eliminated so that only the capacity of the top sheet determined capacitive measurement.

For the most accurate readings, the absorbent layer should be removed completely. However, with further testing, the absorbent layer can potentially still be used with the electrode pad. Such testing would require blood to be applied over long durations of time to ensure that fluid is fully thickened and collected within the absorbent layer to produce steady frequency readings.

Additionally, the electrode pad is designed in such a way so that both capacitive and solid state sensors can be integrated into one electrode pad. With the separation of the pad, the solid state sensors align just outside the width of the feminine hygiene pad. This allows full coverage of the capacitive sensor while simultaneously exposing the solid state sensors. Soldermask was applied to the capacitive sensor to effectively form the dielectric. The following figure depicts the fully integrated system.

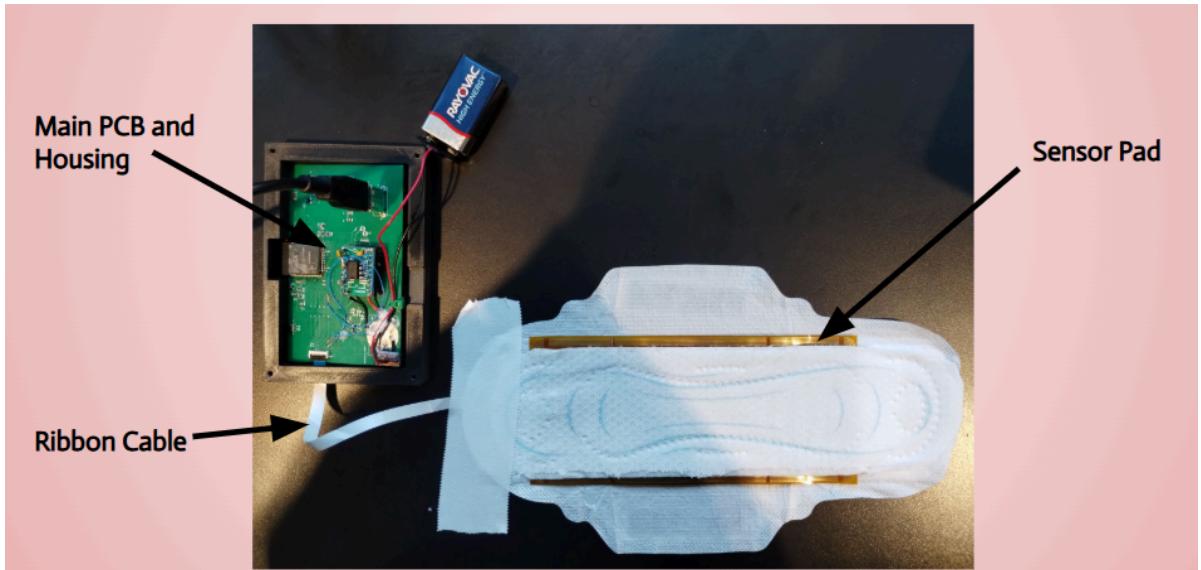


Figure 8.4.1 Full Hardware Integration (produced by Authors)

CHAPTER 9 - TESTING & EVALUATION

9.1 Parts Demo and Testing

The following sections outline the testing procedures performed in regard to critical components.

9.1.1 MCU Testing and Demo Video

To test the MCU without a working PCB prototype we chose to order a development board from TI. This let us test the MCU using all the needed peripherals such as an 32MHz crystal, transmission circuit, and antenna, all things we were hoping to integrate in the PCB stage of testing and not at the part stage of testing. We were successfully able to test the MCU's analog to digital converter with our capacitance sensor, bluetooth low energy transmission and reception, and the MCU itself. It's important to note that the LAUNCHXL-CC2640R2 launchpad that we purchased uses the CC2640R2FRGZ which is the 42 pin package instead of the 32 pin package we ordered for our project, despite this there should be no issues regarding portability to the 32 pin variant.

The launchpad also came equipped with the XDS110 debugger which is extremely useful and easy to use with Arduino's IDE called Arduino IDE. The test for the MCU included three parts, a test of the MCU itself, a test of the Bluetooth Low Energy capability, and a test of the sensor-MCU integration. All three of these tests could have been combined into a single application but I instead decided to separate the BLE test and the sensor test. TI's resource explorer is a very valuable resource when testing their products. Not only is it a great place to find schematics and technical reference manuals but example code, the example code used here was included in the SimpleLink CC2640R2 SDK

(5.30.00.03)[\[61\]](#).

There were three example code projects I chose to help us with testing, simple_peripheral, project_zero, and adcsinglechannel. Simple_peripheral is an application that allows the device to connect and pair with other Bluetooth devices and perform read and write operations over the Bluetooth network. The second project, project_zero is another test application provided by TI that performs very similarly to simple_peripheral but has more in-depth read and write characteristics and UART debug printout. The adcsinglechannel application is a simple application used to test the MCUs internal ADC, this one also prints out to UART and is easy to use. Because this MCU operates using a real time operating system (the TI RTOS) [\[Data-5\]](#) which we are not very familiar with yet, only using embedded C for previous MCU projects, we decided to not make any changes to what TI had provided us with yet in order to get a test of our parts.

For the demo video we chose to use project_zero because of its UART readout that would provide more information on the state of the BLE system. For us to test the BLE capabilities we need to use the BLE stack that TI offers for this line of CC26xx and CC25xx RF MCUs. The stack can be built and flashed to the MCU first and does not need to be reflashed unless explicitly changed. After the stack is flashed the application can then be built and flashed after, what's nice about this method is that the BLE stack stays the same for almost all BLE applications so if we wanted to switch between simple_peripheral and project_zero we would only need to flash the application. After flashing project_zero we can use any Bluetooth device or interface to then scan for our MCU.

Both the phone's bluetooth scanner and the BLE Scanner produced by Bluetooth picked up the MCU's advertisement and allowed connection. When asking to pair via the phone's BT scanner, project_zero attempts to pair by first sending a passkey over UART which can be entered on the device's menu. After that pairing is complete the UART display notifies us that the pairing has completed successfully and this can also be confirmed by browsing the BLE Scanner list of devices and seeing that our device is unable to connect. After unpairing we want to test sending data over BLE, we can use the BLE Scanner app to do this by connecting to the advertising device, using the third custom service and writing a test string to the device. If the string is received it should be displayed on the UART interface for us to check.

9.1.2 Sensor Testing and Demo Video

The sensor we were hoping to test was the capacitive moisture sensor. While our PCB does have a redesigned capacitive sensor on it, the design is very similar to the part which we are testing and this can give us a general idea of how our sensor should act once we begin testing the PCB. The capacitive sensor as explained in chapters 3.1.2 and 6.2 uses a capacitor to measure the strength or size of the dielectric between its electrodes. That means for testing we need to set up a rough experiment with multiple different expected results to determine the sensor's ability.

The integration with the MCU uses the LAUNCHXL-CC2640R2 and the adcsinglechannel test application provided by TI [61]. This program will first check the value of analog pin 0 and broadcast that over UART, then poll the value of analog pin 1 ten times and broadcast the values over UART. The board configuration for this experiment is shown below in figure 9.1.2.1. The first test we ran for the sensor was to compare the ambient readings to the value of analog pin 0 connected to ground. This gives us a baseline of what value we can expect to see when the dielectric is air which comes out to \sim 2.2V. Next we can do a simple test to observe if the sensor value will change in the presence of a different dielectric.

For this test we create another control by wrapping a dry paper towel around the sensor and running the application again, here we get the same value as ambient at \sim 2.2V. Next we can soak the paper towel in water to test the sensor's reading with a different dielectric, the sensor output now is lower at \sim 1.5V. This proves that the sensor readings do change how we would expect them to but it is not a fully comprehensive test. The next test we ran was to gauge just how much the sensor value would change when submerged in varying amounts of water. Because the value of the sensor is not very concrete and depends on the coverage of the electrodes it's important to note that different containers with different dimensions will provide different readings when filled with the same volume of water, this we illustrate in the demo video by performing the next test with two different containers.

The test starts by filling the water up to the bottom of the capacitive sensor and taking a reading. Again this reading should be \sim 2.2V just as we saw before in our control tests which is what we get here. After this measurement we add 100mL of water until the electrodes are both fully submerged. From this test we can see that the sensor value drops very quickly as the electrode is being submerged then levels off to around .93V when fully submerged. With only around 25% of the sensor submerged we got a readout of 1.14V which is significantly lower than the 1.5V measured with the towel test. This data suggests that placement and distance from the dielectric may be more important than quantity of dielectric.

In this paper [62] penetration depth and the role it plays in sensor sensitivity could explain the differences in our test results. With the paper towel test there are more likely to be air gaps within the penetration depth resulting in a higher voltage than a test with only 25% fully submerged. It could also mean that the penetration gap extends much further than the paper towel resulting in a higher voltage. This test also shows us that the sensor value will change relative to the dielectric quantity proving the part does work and work how we expected but it should be noted that much further research and testing will be needed for calibrating and integrating a sensor like this into our project.

9.1.3 Voltage Regulator Testing and Demo Video

To test the boost regulator on a breadboard, we required a breakout board from Adafruit,

as the LTC1682-3.3 boost regulators are only sold in surface mount packages. Testing the voltage regulator allowed us to test two components at the same time: the battery and the voltage regulator. While breadboarding the voltage regulator, since it wasn't being used on a PCB where these regulators are typically used, we had to make our own ground plane by jumping multiple rows together to ensure the shortest connection to ground. It was also important to make sure that the leads on the ceramic capacitors were as short as possible and that the actual capacitors were as close to the IC as possible.

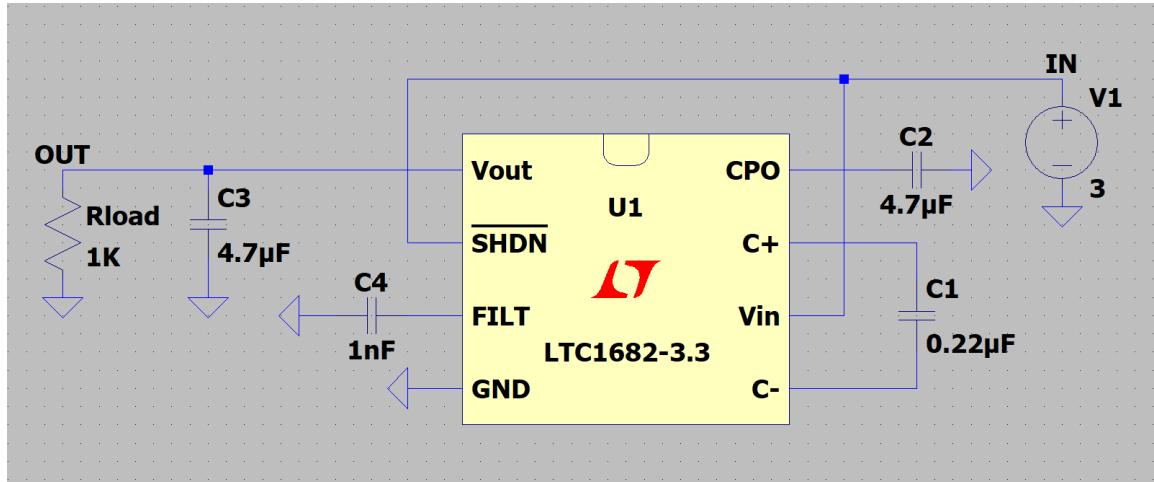


Figure 9.1.3.1 Schematic used to test the boost regulator (created by Authors)

After breadboarding the circuit shown in Figure 9.1.3.1, we were able to test the output of the boost regulator. The output of the boost regulator measured at about 3.293V, whereas the coin cell battery was outputting around 3.222V. This confirmed that our boost regulator was working as intended because it was outputting the expected 3.3V

9.2 Testing

The following sections outline the testing procedures performed in regard to critical subsystems.

9.2.1 Capacitive Sensor Testing

The preliminary tests done on the capacitor sensor for the demo video showed that it performed correctly and produced results similar to what we would expect but lacked the depth needed for our project to succeed. In order to create a capacitive sensor that operates to our needs we will need to perform testing that can be used within the context of our project. This means we need to be able to perform a test with the sensor inside of a menstrual pad and correlate different fluid volume amounts to specific sensor outputs.

To get to that point we need to test multiple different things. The first key test for this sensor would be one with varying electrode widths and gaps, we want a capacitive plate that has a penetration depth large enough to read the moisture level of the pad layer above

it but not too far such that the sensitivity of our sensor is too low due to the amount of air within the penetration depth. Next we need to test the difference in output value with changes to both the 555 timer's frequency and low pass filter values. We cut off a lot of potential range in our sensor by initially setting our lowpass filter too low. The change in signal frequency comes from a paper written on the subject [63] in which it suggests that higher frequencies will cause the dielectric effect caused by electrolytes to dampen and cause less of a change on the capacitive sensor output. However this effect may be beneficial for our project depending on how sensitive we can make our sensor. After that testing is complete we can then start testing the capacitive sensor within a pad. Adding liquid dielectric content relative to the percentage of the weight of the pad could be a great way of getting a more accurate distribution.

After breadboarding of the low pass filter design, inconsistencies in amplitude along with overshoot of the measured output resulted in changing the design to the second version utilizing the CDC. After developing a fully operational breadboard model, paper towels were utilized to act as "pads" in which water was applied, either 1 mL, 2 mL, 3 mL, 4 mL, or 5 mL to determine what volume correlated with each digital output. It was found that each mL applied increased the digital output by approximately 950,000 units. As this value range offered a significant difference, utilizing the CDC appeared to be a very confident design. However, parasitic capacitance when converting to a PCB negatively impacted its performance.

Reverting to a third design, utilizing the frequency of the 555 timer, the base frequency with an empty feminine hygiene pad was found to consistently sit around 90 kHz. In this testing phase, saline was applied in mL increments to the same pad, up to and including 5 mL to simulate full saturation. Through repeated testing, it was found that change in capacitance (and ultimately frequency) was most correlated with area coverage of full absorption. As this is applicable to real applications where long periods of time would inherently result in full absorption, each mL was applied in such a way to speed up the absorption process to simulate true area coverage. This was done by applying the first mL in a central location, and then applying each following mL to be at the perimeter of the previous application, so that it absorbs into a dry portion of the feminine pad. This was found to strongly correlate with consistent frequency values which were easily defined for the respective 75% and 95% threshold capacities. Simulating misapplication in which the saline is applied on the side rather than central, but in a similar fashion simulating full absorption yielded similar results. "Smear" testing in which each applied mL is dropped randomly and rapidly throughout the pad yielded results in which notifications were sent early. However, in reality, this form of application is somewhat unrealistic in regards to how it was simulated, as blood would not be sprayed across the pad when actually used.

9.2.2 Initial Plans for Future Solid State Sensor Testing

The solid state sensor is the simpler sensor of the two in this project. The purpose of the sensor was to simply signal if and when an area of the pad contains enough blood/moisture to short the switch. Because of its simplicity it should be fairly simple to test but not simple to perfect. The sensor needs to be able to short when there is sufficient

moisture which is determinable by us but not short when there is too little or contact through skin. This means we need to finely tune the distance between the contact electrodes and the voltage on the electrodes. Tuning these parameters will mean multiple tests with different electrode areas and gap widths to determine which level of moisture will cause a short, tests on placement of the electrodes to avoid skin as much as possible, and tests on electrode voltage in order to ensure a short is properly detected.

Although ideal, the primary performance of the device is to detect capacity, with the solid state sensors acting as safeties. Because of this, there was a greater focus on the capacitive functionality of the electrode pad rather than the solid state sensors. Since the electrode pad was retrofitted to a store bought pad, rather than integrated with an engineered feminine hygiene pad, the alignment of the concentric rings relative to the top sheet was extremely close, but not perfect. This resulted in loose fabric from the top sheet to cause shorts, even without fluid. Engineering specific feminine hygiene pads that precisely integrated with the electrode pad would resolve this issue, increasing the functionality of the solid state sensors, which can be designed in future iterations of this project.

9.2.3 Testing Environmental Limits of Hardware

To ensure environmental resilience of the electronic device when being used with a feminine hygiene product, the completed hardware will need to be tested to several environmental factors. Hardware functionality will first be tested to ensure that all electrical connections are sufficient and that the device operates as intended. Then, the device will be heated to about 140 °F to ensure it can withstand standard body temperature with a significant degree of clearance (+40 °F) to account for any additional variation, and re-tested to ensure no physical or electrical damage.

In order to test for bodily fluid resiliency, water, salt water, and synthetic blood will be sprayed and/or placed directly onto the device and left for several hours to simulate direct fluid contact for extended periods of time when in use. Afterwards, the fluids will be wiped and cleaned from the PCBs by general purpose disinfectants to test the resiliency of the silicone conformal coating and ensure that the electronic device remains intact. This simulates the user cleaning the device after use for reusability. Finally, the device will be subject to some degree of bending, twisting, and folding to simulate flexibility in real application with feminine hygiene pads, as well as standard wear and tear expected from normal handling and storage of the device when not in use. After each test, electrical performance will be analyzed to ensure functionality. Testing it with these methods allows simulation of real-life application and use from the perspective of the user, while still adhering to current restrictions in regard to direct testing with humans.

Although not directly tested in this fashion, the electrode pad proved to be resilient to both temperature and moisture. In assembling the FPC, a reflow oven was utilized in which the temperature had no impact in regard to base capacitance value and physical degradation, with the exception of slight curvature which can be considered negligible. Since the FPC was subject to temperatures that far exceed human body temperature, it

can be safe to say that it should remain operable. However, continued testing of temperature resilience across long periods of time should still be conducted.

In regard to fluid resilience, since the bulk of electronic components were removed with the latest iteration of the electrode pad, concern for electronic safety is minimized to the scope of the FPC connector along with the four resistors along the base. Due to the inherent nature of testing, both synthetic blood, saline, and isopropyl alcohol was applied and wiped throughout the bulk of the electrode pad. Virtually no physical and electrical degradation was observed.

9.2.4 Testing Software Design

To ensure the functionality and reliability of the software design, we created a comprehensive test plan to cover various aspects of the overall system. The test plan first addressed the Bluetooth Low Energy (BLE) service connection. We verified the reliability and range of BLE by testing the BLE peripheral in a variety of environments. Our testing included both indoor and outdoor locations to evaluate connection performance in enclosed versus open areas. We also tested the connection in noisy environments with potential frequency band interference to ensure the connection was stable and persistent. The goal of this testing was to determine the maximum effective range of BLE communication. BLE scanner apps such as BLE Scanner and LightBlue were used to assess BLE connection quality and signal strength.

The sensor code was also verified to ensure that fluid levels were being calculated accurately and compared correctly to the 75% threshold and the 95% threshold. We used simulated input data to represent fluid levels from 0% to 100% and tested the sensor's accuracy by comparing its readings to expected results. This allowed us to confirm that the sensor data was being correctly processed into percentage values. We verified that the code correctly detected when the threshold was crossed and that it executed the appropriate notification handling steps. The fluid volume readings from the sensor were found to be accurate within a 5% margin of the actual values.

Additionally, we tested whether BLE notifications were displayed in a timely manner on both Android and iOS mobile devices to ensure cross-platform compatibility and effectiveness. Notifications were confirmed to be triggered and displayed on connected devices within 1 second of the threshold being reached.

9.2.5 Testing Integration with Feminine Hygiene Pad

Once testing of complete device functionality was complete (to include full hardware and software integration), integration with a feminine hygiene pad was tested to verify compatibility and that the physical constraints specified have been met. Feminine hygiene pads were purchased, along with the medical grade silicone adhesives for the main PCB.

The pads were carefully separated into its four layers so that the sensor pad PCB(s) can be placed in its respective location(s).

Once placed, the layers were re-assembled into the feminine hygiene pad. Then, the main PCB was attached underneath the pad via the medical grade silicone adhesives. Successful integration of the device with a feminine hygiene pad indicates that the physical constraints of the project have been met. Once fully assembled, the integrated product was then tested to adhere to the expected performance metrics stated in Chapter 2.

With this integration, it was found that the absorbent layer created variability in absorption due to containing a gel that thickened and collected the fluid applied. For the purposes of conceptual testing, the absorbent layer was omitted. However, future testing involving longer periods of time can be implemented with the absorbent layer to allow appropriate thickening and collection of the gel.

9.2.6 Testing of Response Time and Capability

The first performance metric we tested encapsulated the primary function of the project: ensuring that a user was directly notified prior to leakage from a feminine hygiene pad. This required a rapid response time from the MCU's transmission to the app, with notifications expected to be delivered at the 75% and 95% thresholds. As stated in Chapter 2, transmission was expected to occur within 1 second (ideally close to instantaneous) after these thresholds were crossed. To achieve this, we first determined the total capacity in milliliters (mL) of the feminine hygiene pad, using either product documentation or direct testing.

Once the total capacity was known, we calculated the 75% and 95% threshold values in mL. A syringe with mL increments was then filled with synthetic blood, and droplets were slowly applied to the pad. When the applied blood volume reached the 75% capacity value, a notification was expected to appear on the connected device via the software application.

We recorded the time difference between the moment the threshold was crossed and the notification alert. The same process was repeated for the 95% threshold. A time difference less than or equal to 1 second indicated successful performance, meeting the expected response time metric.

9.2.7 Testing of Volume Accuracy

Testing the response time also allowed us to verify the volume accuracy metric. Assuming the transmission response time was within 1 second of crossing the specified thresholds, we calculated volume accuracy at 75% and 95% by comparing the actual blood volume dispensed from the syringe to the expected volume at each threshold.

A volume difference within 1 mL of the expected value indicated that the device met the accuracy specification outlined in Chapter 2. The ideal case in which the notification was sent within 0.25 mL (noted in green in Table 9.2.8.1) was observed in most cases, with

the occasional early notification occurring (noted in yellow in Table 9.2.8.1) but remaining within the 1 mL allowable tolerance. Notifications that were outside the 1 mL allowable tolerance are highlighted red. There was only one instance out of thirteen runs that this occurred.

9.2.8 Testing of Performance Reliability

After verifying response time and volume accuracy, we tested the performance reliability of the system to ensure these metrics were met consistently. Reliability was critical for establishing user trust in the device and minimizing failures during usage. As this was a prototype developed for Senior Design, we aimed to achieve a reliability metric of at least 90% by the end of the project. Future iterations beyond Senior Design could aim to improve this reliability to 99% to maximize customer satisfaction. We verified performance reliability through multiple iterations of the previously described tests. This phase of testing was only conducted after the prototype demonstrated full functionality and consistently met accuracy and response time expectations. If performance reliability fell below 90%, we performed additional hardware or software troubleshooting or considered redesigns involving different technologies or components.

Utilizing thirteen consecutive test runs, the device was capable of meeting the required engineering specifications with 92.3% reliability as summarized in the following table.

TRIAL	1	2	3	4	5	6	7	8	9	10	11	12	13
75% Notif (mL)	~3.5	~3.5	~3.5	~3.5	~3.5	~3.5	~3	~3.5	~3.5	~3.5	~3.5	~3.5	~3
95% Notif (mL)	~4.5	~4.5	~4.5	~4.5	~4	~4.5	~4	~4.5	~4.5	~4.5	~4.5	~4.5	~3
Response Time (s)	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1

Figure 9.2.8.1 Data Summary of 13 Consecutive Tests (created by Authors)

The instances where our notifications were earlier than expected can be attributed to a few factors. Our sensor's frequency output is not directly correlated with the volumetric amount of dielectric added to the absorbent pad. Instead, it is influenced by the dielectric volume that intersects with the capacitor's electric field. Consequently, the correlation is stronger between frequency and the percentage of the absorbent pad covered by the dielectric.

In our tests, the fluid was applied to the pads in a manner that accelerates absorption, simulating full saturation over a much shorter time. However, this process is imprecise, and variability in the pads introduces irregularities in the percentage of coverage. To

ensure reliability, we set the notification thresholds using upper bounds, prioritizing the avoidance of missed notifications. As a result, these thresholds, combined with pad irregularities, increase the likelihood of early notifications rather than late ones.

CHAPTER 10 - ADMINISTRATIVE CONTENT

10.1 Budget & Financing

As our project is a potential product down the line, we would like to try to keep the cost of materials as low as possible, so that the product could be sold for a reasonable price in order to attract customers. To achieve this, establishing a budget that effectively allocates resources can allow our team to develop a product that meets the project's specifications and requirements while simultaneously minimizing cost. The table below represents a tentative budget that meets these expectations. Additionally, a Bill of Materials that meets the budget expectations is presented.

10.2 Table of Work Distributions

To effectively achieve and accomplish the objectives of this project, it is essential to establish a clear understanding of how tasks and responsibilities are distributed among team members. Table 10.2.1 represents a detailed breakdown of work distribution, indicating each member's assigned roles, responsibilities, and tasks.

This provides a structure that facilitates better planning and coordination while simultaneously ensuring that each aspect of the project is managed efficiently to streamline workflow and enhance productivity. Work distributions were decided as a group based on individual preferences and strengths. Table 10.2.1 displays the roles given to each member with primary and secondary responsibilities.

Table 10.2.2 represents the research responsibilities of each individual on the team. While being similar to the previous figure, it is not a direct reflection as additional topics and information must be researched beyond the physical hardware being used in this project, including design methods, implementation, schematic design, integration, testing requirements, etc for each respective aspect of the design. Thus, additional adjustments were included to reflect these requirements.

10.3 Project Milestones

In order to deliver a demonstrable product by the end of Senior Design and meet the time constraints of the project, milestones for project progress must be clearly defined and established. These milestones act as a tentative marker throughout the engineering process, indicating the current status of where the project is within its development phase. Table 10.3.1 represents these milestones with clear dates and deadlines throughout the duration of SD1 and SD2.

Number	Part	Cost	Quantity	Subtotal	Budget
1	Voltage Regulator	\$1.17	1	\$1.17	\$2.00
2	Buttons	\$0.70	2	\$1.40	\$2.00
3	Battery Holder	\$0.61	1	\$0.61	\$1.00
4	Flex Cable Connector	\$0.53	2	\$1.06	\$2.00
5	USB Connector	\$1.30	1	\$1.30	\$2.00
6	555 Timer	\$0.85	1	\$0.85	\$1.00
7	NPN Transistor	\$0.03	2	\$0.06	\$1.00
8	6 Inch Ribbon Cable	\$3.84	1	\$3.84	\$5.00
10	SMD Resistors and Capacitors	\$0.03	1	\$0.03	\$1.00
11	Rigid PCB	\$1.60	1	\$1.60	\$3.00
12	Flexible PCB	\$6.78	1	\$6.78	\$10.00
13	Battery	\$1.50	1	\$1.50	\$5.00
14	ESP 32	\$5.00	1	\$5.00	\$5.00
					\$25.20
					\$40.00

Figure 10.1.1 EASE Bill of Materials

Component	Primary Responsibility	Secondary Responsibility
Sensor	Matthew Poole	Alexander Nguyen
Transmitter	Dillon Sardarsingh	David Garzon
Software Application	David Garzon	Dillon Sardarsingh
MCU	Matthew Poole	David Garzon
Power Supply	Dillon Sardarsingh	Alexander Nguyen
Housing Unit / PCB	Alexander Nguyen	Matthew Poole
Administrative	Alexander Nguyen	

Figure 10.2.1 EASE Work Distribution Table

Component	Primary Responsibility	Secondary Responsibility
Battery/Power Supply	Dillon Sardarsingh	Alexander Nguyen
Transmitter	Dillon Sardarsingh	David Garzon
Software Application	David Garzon	Dillon Sardarsingh
MCU	Matthew Poole	David Garzon
Sensor	Matthew Poole	Alexander Nguyen
Housing Unit / PCB	Alexander Nguyen	Matthew Poole
Testing Procedure/Equipment	Alexander Nguyen	David Garzon
Build Equipment	Collaborative	

Figure 10.2.2 EASE Research Distribution Table

Senior Design 1	
Deadline	Milestone
August 26, 2024	Project Idea Brainstorming
September 3, 2024	Project Selection
September 5, 2024	Committee Formation
September 6, 2024	Divide & Conquer Document
September 20, 2024	Component Research, Investigation and Selection
October 11, 2024	Standards and Design Constraints
October 24, 2024	Comparisons
October 25, 2024	60 Page Document Submission
November 1, 2024	Hardware Design and Software Design
November 15, 2024	System Fabrication

November 26, 2024	System Testing
Senior Design 2	
Date	Milestone
January 24, 2025	PCB Layout
February 7, 2025	PCB Review and Order
February 14, 2025	PCB Assembly
February 15, 2025	Integrate Software
February 26, 2025	CDR Presentation
March 8, 2025	Midterm Demonstration
March 8, 2025	Redesign PCB, Troubleshoot, and Debug Code
March 8, 2025	PCB Reorder
March 28, 2025	8-Page Conference Paper
April 7, 2025	Final Testing
April 12, 2025	Final Project Review Submission
April 17, 2025	Live Demonstration
April 18, 2025	Senior Design Showcase

Figure 10.3.1 EASE Project Milestone Table

CHAPTER 11 - CONCLUSION

The development of this smart feminine hygiene product has demonstrated the potential of integrating technology into everyday health products to improve comfort and convenience for women. By addressing the common issue of unpredictable menstrual flow, our project aims to eliminate the stress and embarrassment associated with unexpected leaks. The final product, equipped with real-time fluid monitoring and Bluetooth Low Energy (BLE) notifications, empowers users to manage their menstrual cycles more effectively.

The solution offers timely alerts to users when a pad is nearing its absorption limit, allowing for proactive changes and reducing the likelihood of leaks. This not only provides a practical solution to a widespread issue but also highlights the role that innovative design can play in enhancing everyday products.

Our research, design, and testing phases provided valuable insights into the technical challenges and considerations involved in creating a smart wearable device. While there were constraints in terms of manufacturability, comfort, and maintaining a discreet design, the project showcased how these challenges could be addressed without compromising functionality. This project also opens the door for further exploration into smart feminine hygiene products, potentially leading to future advancements in menstrual health technology.

However, further limitations have been discovered as part of the research and design conducted as physical prototyping may reveal complications in regard to physical implementation of the PCBs designed. Maximizing performance may sacrifice discreteness in the form of weight and bulk, potentially violating the physical constraints necessary to properly integrate the product. Additionally, sensitivity of the capacitive sensors may present an issue as the expected volume it is expected to measure is extremely low with narrow degrees of freedom. Determining an optimal balance that presents a fully functional electronic system that meets its expected performance metrics without significantly sacrificing the physical necessities of its application will need to be identified and determined as the product is constructed and prototyped in Senior Design 2.

Overall, our research successfully demonstrates proof of concept that has the potential to contribute to a larger conversation about improving women's health and wellness through technology. By focusing on a simple yet impactful problem, we hope to inspire future innovations that make menstrual management easier, less stressful, and more empowering for women everywhere.

APPENDICES

Appendix A - References

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Appendix B - Copyright Permission

[B-1]

Alexander Nguyen
To: support@jlcpcb.com
Mon 11/25/2024 1:44 PM

Good afternoon,

My team and I are developing a senior design project in which we will order a flexible PCB from JLCPCB. We were wondering if you would be willing to give permission for our team to use the following images from the JLCPCB website regarding flexible PCB design constraints in our Senior Design report:

Copyright Images Permission Request

JLCFPC.zip

Some content in this message has been blocked because the sender isn't in your Safe senders list.
Retention: UCF Delete after 10 Years (10 years) Expires: Sun 11/26/2034 11:27 AM

JLCFPC.zip
Downloaded

Dear Alexandre,

We have received your letter of undertaking, and attached to this email is a file package containing images of flexible PCBs from our company. We appreciate your interest in using our images for your academic research.

To ensure the images are used in alignment with our brand identity and to support your research efforts, we kindly request the opportunity to preview the relevant sections of the completed report or review the final document. If needed, we are more than happy to provide further assistance to help facilitate your work.

Thank you for your cooperation, and please feel free to reach out if you have any questions.

Best regards,

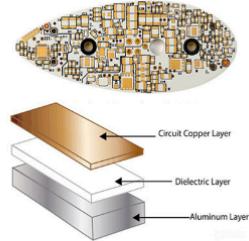
Syran

Attach a file ▾
Reply Forward

[B-2]

Good afternoon,

As part of a senior design project, we have been researching different types of PCBs. In our report, my team and I were hoping to utilize the following image from your site:



We were wondering if you would willing to grant us permission to use it in our report with appropriate citation.

Thank you for your time.

Sincerely,

Alexander Nguyen

[B-3]

Good afternoon,

As part of a senior design project, our team was wondering if you would grant us permission to utilize the following image in our research report, with proper citation:



Thank you for your time. We look forward to hearing from you.

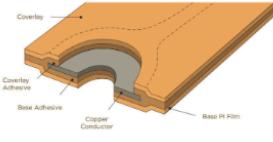
Sincerely,

Alexander Nguyen

[B-4]

Image Use Request

My team and I are developing a senior design project that will be utilizing flexible PCBs. As part of the research report, we were hoping to include the following image and was wondering if you would be willing to grant us permission to use it in our report.



Typical single-layer flex circuit stack-up.
(from <https://resources.altium.com/p/introduction-flex-pcb-materials>)

Thank you for your time and consideration. I look forward to hearing from you.

Sincerely,
Alexander Nguyen

student support <studentsupport@altium.com>
To: © Alexander Nguyen
Retention: UCF Delete after 10 Years (10 years) Expires: Fri 11/24/2034 9:16 AM

Hi there,
You should cite the Altium site if you will use the image in the report. As long as it is cited on the Altium page that the image is on, then you should be fine.
Best,
The Altium Education Team

...

[Reply](#) [Forward](#)

Appendix C - Data Sheet

[Data-1] SWRS204C - CC2640R2F SimpleLink™ Bluetooth® 5.1 Low Energy Wireless MCU

[Data-2] swcu117i - CC13x0, CC26x0 SimpleLink™ Wireless MCU Technical Reference Manual

[Data-3] swra495k - Crystal Oscillator and Crystal Selection for the CC13xx, CC26xx, and CC23xx Family of Wireless MCUs

[Data-4] swra640h - CC13xx/CC26xx Hardware Configuration and PCB Design Considerations

[Data-5] swru393e - CC26x0 SimpleLink™ Bluetooth® low energy Software Stack 2.2.x

[Data-6] swra351b - Antenna Selection Quick Guide

Appendix D - AI-Based Prompts and Outcomes

[A-1] Prompt: What are the different types of PCBs that exist

ChatGPT Outcome: PCBs come in several types based on their construction, material, and application requirements. Here's a look at the most common types of PCBs:

1. Single-Sided PCBs

- **Description:** These PCBs have only one layer of conductive material (copper) on one side of the board. Components are mounted on the other side.
- **Use Cases:** Used for simple, low-density designs where cost is a concern, such as in calculators, power supplies, and LED boards.

2. Double-Sided PCBs

- **Description:** Conductive material is applied on both sides of the PCB. Components can be mounted on either side, with vias (holes) allowing connections between layers.
- **Use Cases:** Commonly used in automotive dashboards, industrial controls, and many consumer electronics where moderate complexity is needed.

3. Multilayer PCBs

- **Description:** These PCBs have three or more layers of conductive material. Layers are separated by insulating materials and bonded together.
- **Use Cases:** Ideal for complex applications requiring high signal integrity, such as in computers, servers, medical devices, and telecom systems.

4. Rigid PCBs

- **Description:** Made from rigid substrate materials, these PCBs are inflexible and maintain their shape. They are available in single, double, or multiple layers.
- **Use Cases:** Common in most consumer electronics (e.g., TVs, laptops) and industrial machinery, where a rigid structure is preferred.

5. Flexible PCBs (Flex PCBs)

- **Description:** Made from flexible materials like polyimide, allowing the PCB to bend and flex. Flex PCBs can be single-sided, double-sided, or multilayer.
- **Use Cases:** Used in devices requiring flexibility, like wearables, foldable displays, medical devices, and compact devices with limited space.

6. Rigid-Flex PCBs

- **Description:** These combine both rigid and flexible board areas in one design, offering both rigidity and flexibility in a single board.

- **Use Cases:** Common in aerospace, military, and medical applications where compact and lightweight designs with reliability in harsh conditions are required.

7. High-Frequency PCBs

- **Description:** Built using materials that support high-frequency signals (such as PTFE), ensuring minimal signal loss at high frequencies (typically above 1 GHz).
- **Use Cases:** Used in RF applications, microwave circuits, satellite communications, and GPS systems where signal integrity is critical.

8. Aluminum-Backed PCBs

- **Description:** Have an aluminum base instead of fiberglass, allowing excellent heat dissipation. Often layered with a thermal insulating layer and conductive layer.
- **Use Cases:** Ideal for high-power applications such as LED lighting, power supplies, and automotive lighting, where heat management is essential.

9. HDI (High-Density Interconnect) PCBs

- **Description:** These PCBs feature finer lines, smaller vias, and denser connection points, enabling more components and connections in a smaller area.
- **Use Cases:** Common in compact, high-performance devices like smartphones, tablets, and wearables where space and weight are limited.

10. Metal Core PCBs (MCPCBs)

- **Description:** Similar to aluminum PCBs but can have cores made of different metals (e.g., copper). They offer enhanced heat dissipation and are available in single- and multi-layer configurations.
- **Use Cases:** Used in high-power applications, such as motor control, automotive electronics, and industrial lighting.

11. Flexible-Rigid Hybrid PCBs

- **Description:** A newer type where both flexible and rigid sections are layered and laminated together, offering durability while allowing limited flexibility.
- **Use Cases:** Used in applications that require movement and durability, such as in industrial robotics and some medical equipment.

Each type of PCB is designed to meet specific performance, cost, and physical requirements, enabling designers to select the best PCB type for the application at hand.

[A-2] Prompt: Assist in creating the basic framework for a C file I could use in Code Composer Studio. I am going to use that framework to later program a sensor on my TI board, however I only need the basic framework

GitHub Copilot Outcome:

```
#include <stdint.h>
#include <stdbool.h>
#include "inc/hw_memmap.h"
#include "inc/hw_types.h"
#include "driverlib/sysctl.h"
#include "driverlib/gpio.h"

// Function prototypes
void setup(void);
void loop(void);

int main(void)
{
    // Set the clocking to run directly from the crystal at 50MHz.
    SysCtlClockSet(SYSCTL_SYSDIV_4 | SYSCTL_USE_PLL | SYSCTL_OSC_MAIN |
SYSCTL_XTAL_16MHZ);

    // Call the setup function
    setup();

    // Main loop
    while (1)
    {
        loop();
    }
}

void setup(void)
{
    // Initialize the peripherals here
    SysCtlPeripheralEnable(SYSCTL_PERIPH_GPIOF);
    GPIOPinTypeGPIOOutput(GPIO_PORTF_BASE, GPIO_PIN_1 | GPIO_PIN_2 |
GPIO_PIN_3);
}

void loop(void)
{
    // Main code to run repeatedly
    GPIOPinWrite(GPIO_PORTF_BASE, GPIO_PIN_2, GPIO_PIN_2);
    SysCtlDelay(2000000);
    GPIOPinWrite(GPIO_PORTF_BASE, GPIO_PIN_2, 0);
    SysCtlDelay(2000000);
}
```

[A-3] Prompt: Can you create a table comparing these sensors here are the reference paragraphs (Report section 3.1.2 Sensor)

Microsoft Copilot Outcome:

Here's a comparison table of the different sensor options based on the provided information:

Feature	Time of Flight Sensors	Capacitance Sensors	Pressure Sensors	Float Level Sensors	Solid State Sensors
Working Principle	Measures time for a pulse to return	Measures changes in capacitance	Measures pressure changes	Measures movement of a buoyant part	Detects shorted contacts
Accuracy	High in controlled environments	Less accurate, needs calibration	Versatile and reliable	Needs defined, static fluid container	Discrete data, less continuous accuracy
Size and Comfort	Large, not suited for small applications	Works well in small environments	Can be large, difficult to implement in small spaces	Not intuitive for small scale	Flexible implementation
Simplicity	Complex setup required	Simple, easy to use unconventionally	Varies by type (e.g., piston, capacitive, piezoelectric)	Simple but needs auxiliary sensor	Very simple implementation

Container Requirements	Rigid, known dimensions	Needs calibration based on container	Does not always need container dimensions	Needs static container	Depends on liquid conductivity
Environmental Dependency	Sensitive to environment	Needs dielectric constant of liquid	Can work with varied environments	Limited to specific container setups	Requires conductive liquid
Best Use Case	Controlled environments	Small, defined environments	Versatile applications	Large, defined fluid containers	Flexible applications
Drawbacks	Needs controlled environment, large	Less accurate, needs calibration	Can be large, difficult in small spaces	Not intuitive for small scale, needs static container	Discrete data, exposed contacts wear over time

Summary

Time of Flight Sensors:

Accurate in controlled environments, large, not suited for small applications.

Capacitance Sensors:

Simple, works well in small environments, less accurate, needs calibration.

Pressure Sensors:

Versatile, reliable, but can be large and difficult to implement in small spaces.

Float Level Sensors:

Simple, needs static container, not intuitive for small scale applications.

Solid State Sensors:

Very simple, flexible implementation, discrete data, exposed contacts may wear over time.

This table highlights the key differences and features of each sensor type, helping you determine the best option for your project based on your specific requirements. If you have any more questions or need further details, feel free to ask! 😊

[A-4] Prompt: What kinds of batteries/power supplies would you consider when designing a product that would go inside of a feminine pad that detects when it is about to leak?

ChatGPT Outcome:

For a product that goes inside a feminine pad and detects when it is about to leak, several key considerations will influence the choice of batteries or power supplies. The ideal power source should be compact, lightweight, safe, reliable, and have a lifespan that matches the typical usage cycle of the product. Here are some options to consider:

1. **Coin Cell Batteries (Button Cells):**

- **Pros:** Small, lightweight, and commonly used in wearable and low-power devices.
- **Cons:** Limited power capacity might not be suitable for devices with continuous monitoring.
- **Battery Types:** Lithium coin cells (e.g., CR2032) are commonly used due to their relatively high energy density and long shelf life.

2. **Thin-Film Batteries:**

- **Pros:** Flexible, thin, and lightweight, which can be embedded easily into the pad material. They are also relatively safe.
- **Cons:** Limited energy capacity, which may restrict usage to short periods or require highly efficient power management.

3. **Micro-Batteries:**

- **Pros:** These are very small in size and can provide sufficient power for low-energy sensors. Micro-batteries can be integrated into the structure of the pad.

- **Cons:** They may be more expensive compared to other types of batteries and are less widely available.

4. Printed Batteries:

- **Pros:** These are ultra-thin and flexible batteries made using printing technology, perfect for disposable or short-use products like feminine pads.
- **Cons:** They have lower power density compared to traditional batteries and might only be suitable for low-power applications.

5. Energy Harvesting Techniques:

- **Pros:** For continuous monitoring, using energy harvested from body heat, motion, or even moisture itself could provide a sustainable power source, reducing the need for an external battery.
- **Cons:** These techniques are still developing and may not yet provide the consistent power levels needed for reliable sensing.

6. Supercapacitors:

- **Pros:** They can deliver quick bursts of power and be charged relatively quickly. Their thin form factor might allow them to be integrated into the product.
- **Cons:** Limited energy storage capacity compared to traditional batteries might limit their use unless combined with energy harvesting.

Key Design Considerations:

- **Safety:** The battery must be non-toxic and safe for skin contact.
- **Lifespan:** Ideally, the power supply should last for the duration of the pad's usage period (usually a few hours to a day) without needing replacement.
- **Disposable Nature:** If the pad itself is disposable, it is preferable to have a power source that is also disposable or biodegradable.
- **Cost:** Since feminine pads are single-use items, keeping the cost low for the battery or power supply is essential for commercial viability.

Given these factors, thin-film or printed batteries might be the most practical option, as they align with the requirements of flexibility, safety, and disposability. Energy harvesting could be a future-proof approach if the technology advances enough to provide consistent power for the device.