Wireless ECG

ECE445 Project Design Document

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1. Introduction

1.1 Overview of Electrocardiogram (ECG)

Electrocardiogram, often referred to as ECG, is a visualization (gram) of electricity (electro) that flows through one's heart (cardio). The traditional 12-lead ECG, using 10 electrodes, is the most widely used in an accurate diagnosis of heart abnormalities. An electrode is analogous to a single voltage node, and a lead can be thought of as a vector pointing from one electrode to another. ECG shows the depolarization wave, which is a wave of positive charges. When the depolarization wave is along the direction of the lead vector direction, the waveform would be positive on the graph.

There are 4 limb electrodes (Left Arm, Right Arm, Left Leg, Right Leg) and 6 precordial electrodes (V1~V6). 12 leads are derived from linear combinations of these 10 electrodes, thus the name 12-lead ECG. Combining leads in different directions provides a three-dimensional view of the heart, enabling doctors to monitor heart activities and locate exact causes of heart abnormalities such as arrhythmia, heart attacks, and pericarditis.

While the heart is a repetitive series of pulses, one pulse can be decomposed into different segments that correspond to various events occurring during a heartbeat. A period of wave is referred to as PQRST wave (see figure 1).
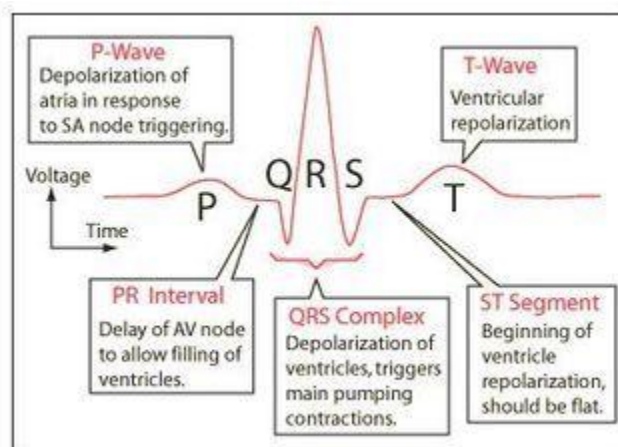

Figure 1. PQRST wave and how it relates to heart activities. Adapted from [1].

Criteria such as interval time length, amplitude, are used for each interval to detect abnormalities.

1.2 Problem

Conventional 12-lead ECG involves ten electrodes that need to be placed on the chest of a patient. These wires are often tedious to deal with and would be inconvenient for doctors to deal with them. This issue particularly becomes problematic in emergency situations, where every second matters to the patient.

There are some products that have been developed to help resolve the issue. Apple watch has an ECG app that can monitor the heart signal, where the user can hold the digital crown with a finger such that a loop is formed. The limitation is that it only uses a single lead. Similarly, Zio Patch and BardyDx CAM can only measure ECG with one lead. These devices are single-use, which are not efficient in terms of replaceability.

Figure 2. Existing products - Apple Watch (Left), ZioPatch (middle), BardyDx CAM (right). Adapted from [2],[3],[4]

1.3 Solution

Our project's goal is to develop a wireless ECG that does not require leads to be connected to the main monitoring device that is far away from the body. We aim to primarily focus on convenience and replaceability.

Convenience is achieved by minimizing the wires involved in the process of setup. The device will involve a central hub and three wired nodes. The purpose of nodes is to measure the body surface potential, and that information is processed in the hub. The hub processes and converts the analog voltage signal to digital data, and the data is transmitted wirelessly to the monitor through Bluetooth protocol. Since ECG waveforms are obtained by measuring the voltage, a ground node in a distance from the measuring nodes is necessary to act as a reference point during measurements. In order to minimize the wires required for the three nodes, retractable cables will be used such that the cables are at their shortest length when not in use. This also accounts for the fact that different people have different body sizes, so doctors simply need to pull the wires to whatever length necessary.

Figure 3. A retractable cable. Adapted from [5]

Replaceability is achieved by using conventional ECG patches that can stick onto the body surface. An ECG patch is made of a circular sheet of adhesives and a metal at the center. This metal can be attached to the node wire, resembling the shape of metal clip buttons. In this way, the ECG patches become replaceable and the device becomes reusable by simply replacing the ECG patches. We also aim to make the battery replaceable to achieve multi-usability for different patients.
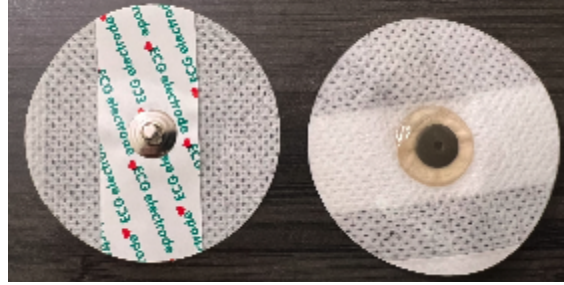
Figure 4. ECG patches - front (left) and back (right)

It is necessary to acknowledge that the traditional 12-lead ECG provides a more accurate and detailed heart diagnosis. This is because more leads over different parts of the body can provide a 3D view of the heart and are hence able to spot the exact location of heart abnormalities. Given the scope and time limitation for our project, we aim to implement a 3-lead (4 electrodes) ECG which transmits and displays the ECG waveform while enhancing the reusability of the device.

We expect two primary uses of this device. One is to be used in emergency situations for quick diagnosis, where time is the absolute element. Also, it can be used in normal monitoring of heartbeat, where one can look for heart rate and strength of a signal from the heart muscle, often monitored by a rehab trainer.
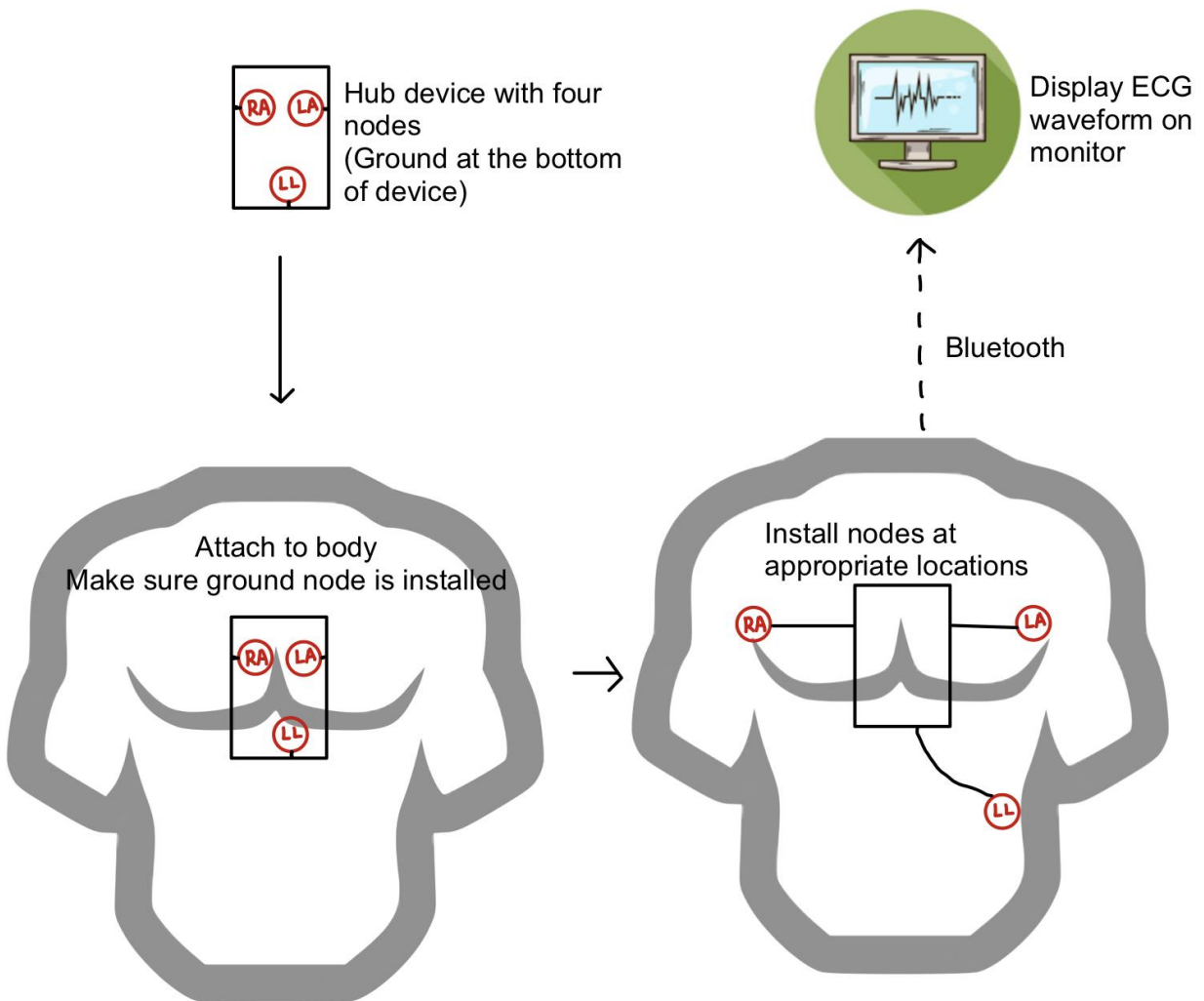
1.4 Visual Aid

Hub device with four nodes
(Ground at the bottom of device)

Display ECG waveform on monitor

Bluetooth

Attach to body
Make sure ground node is installed

Install nodes at appropriate locations

Figure 5. High-level visual representation of the device usage

1.5 High-Level Requirements

1. The device should successfully display 3 ECG waveforms on the computer by filtering the signal with cutoff frequencies of 1Hz and 30Hz, with data sampling frequency of at least 200Hz.
2. The data transmission rate for transmission from the hub to the computer/phone should be at least 18 Kbps or higher when the device is 5m away from the monitor.
3. The data transmission delay for transmission from the hub to the computer/phone should be within 10 seconds.
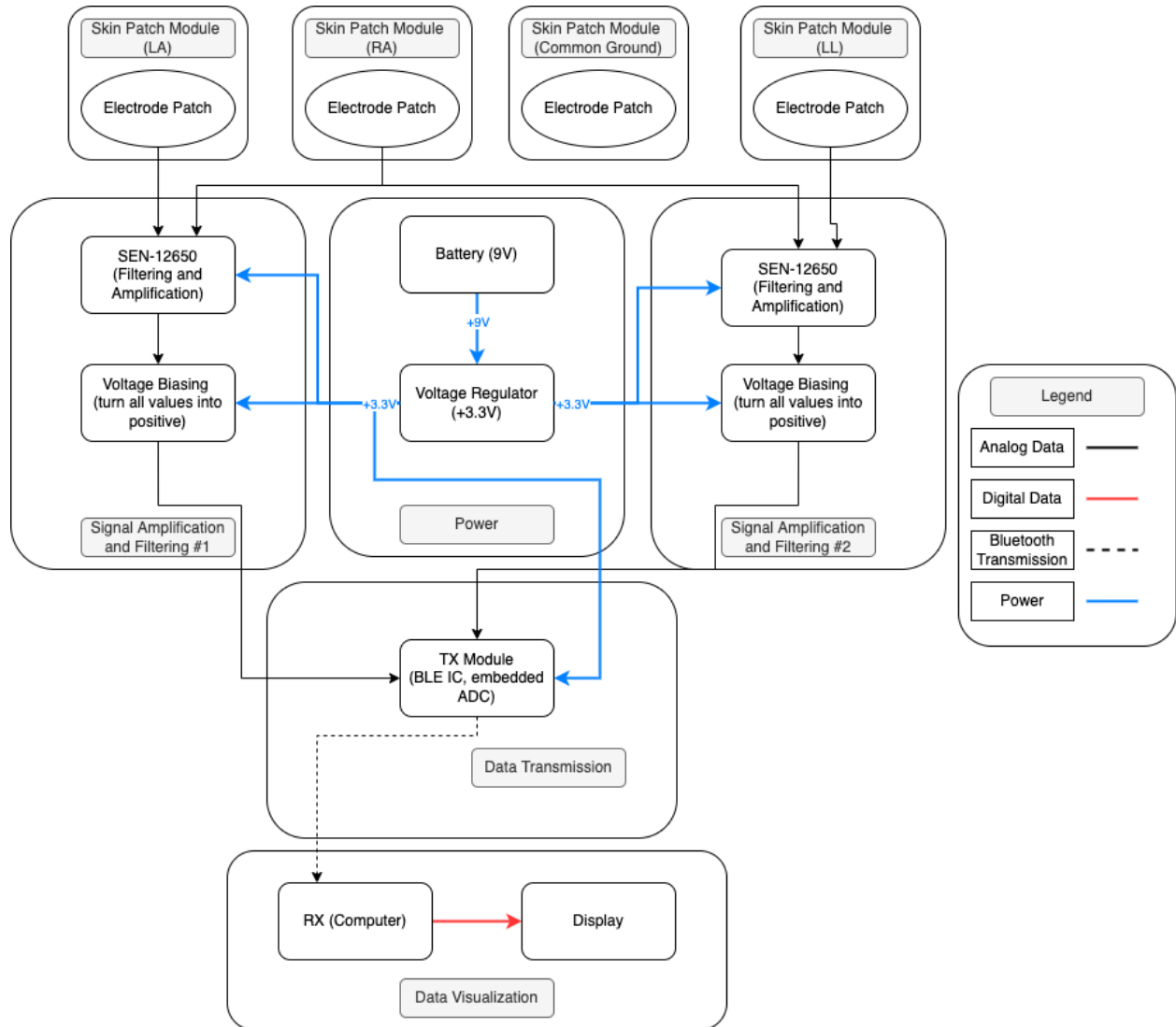
2. Design

2.1 Block Diagram

Figure 6. Block Diagram of the design
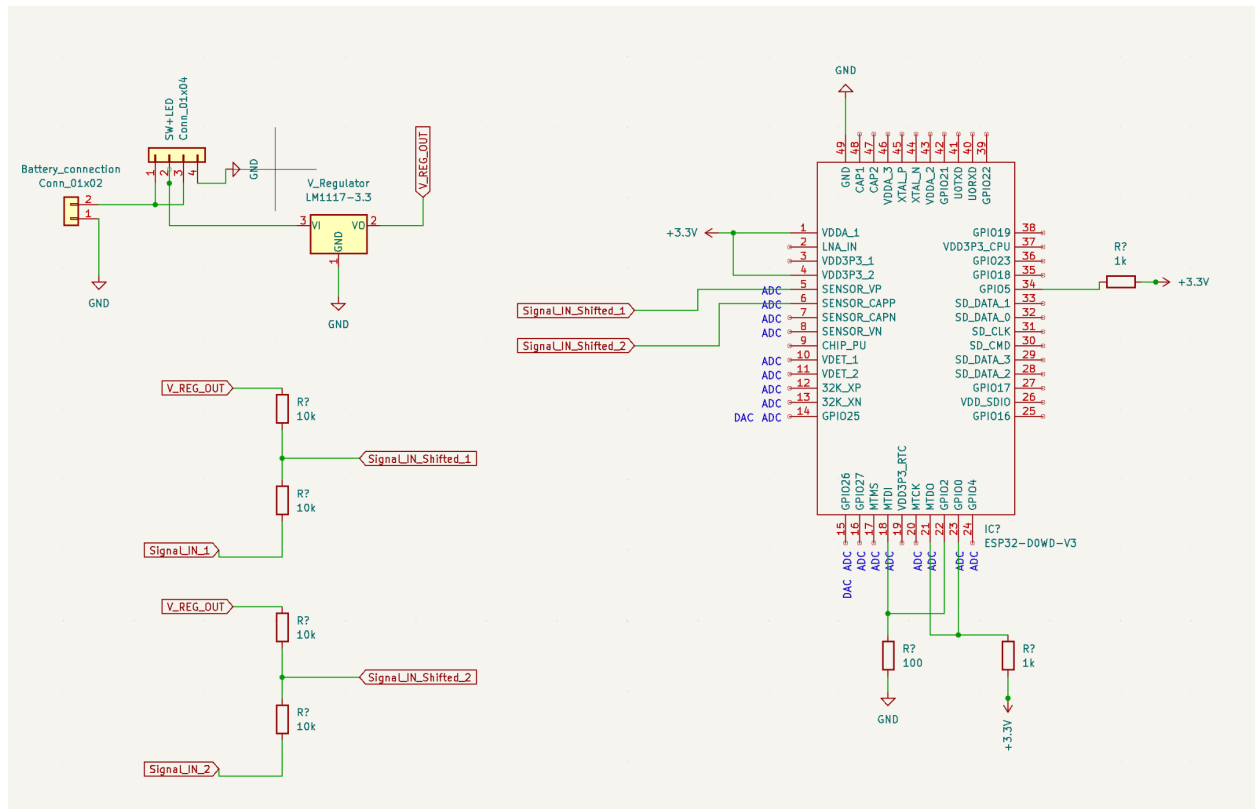
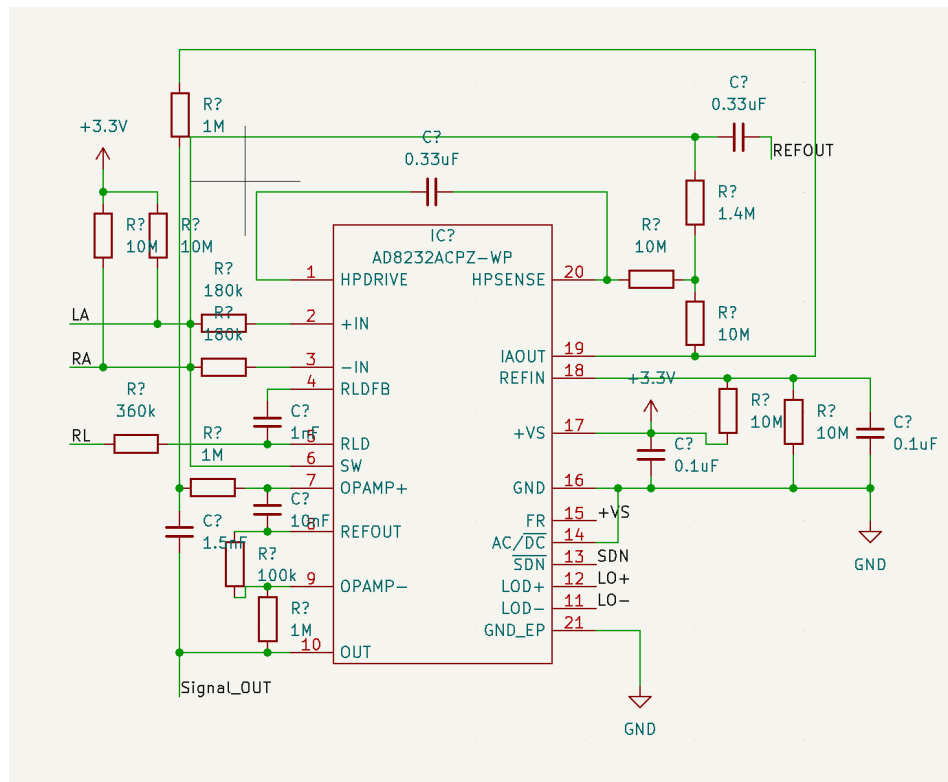Figure 7. Circuit Schematic of the device

Figure 8. Circuit Schematic of AD8232 with its typical implementation (SEN-12650)

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2.2 Physical Design
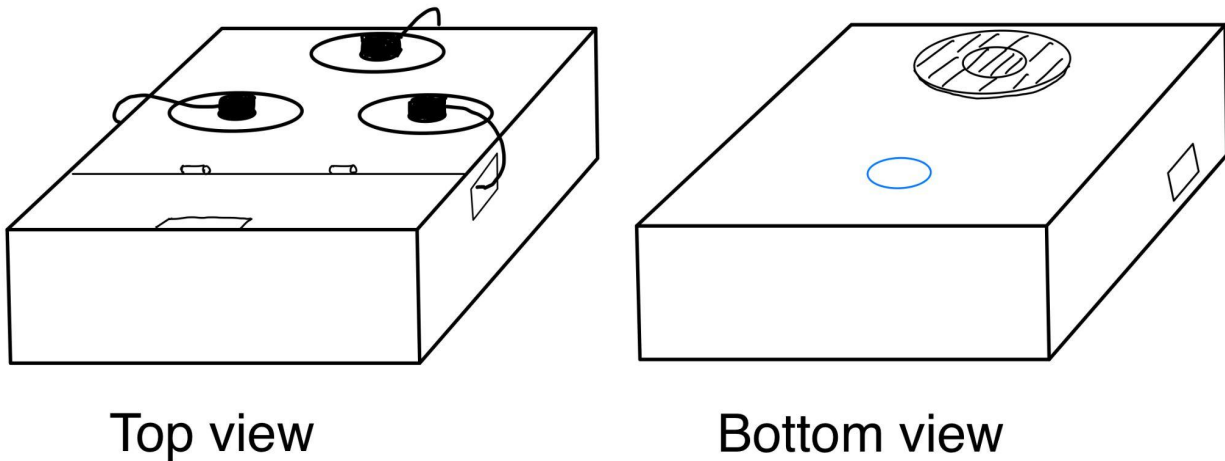

Top view   Bottom view

Figure 9. Top and bottom view of the device

- Small holes on the side of the device are used to guide wires to the ECG patches (electrodes).

- There is a small part of the top cover to be lifted such that the battery can be replaced. The top part includes a thin magnetic strip such that the cap does not fall off when the device is installed on the body.

- The bottom shows the ground node (in black) and a mounting surface to install an extra ECG patch (in blue) which simply serves as an adhesive.

2.3 Module Descriptions

2.3.1 Power Module

A 9-volt battery is used to operate the entire system such that it is replaceable when it runs out of battery. It is distributed into two voltage regulators: one voltage regulator provides +3.3V for the operational amplifier to operate, and the other provides +3.3V to the voltage biasing circuit, ADC, and BLE ICs. The battery is connected to Vin, which is then regulated by LM1117-3.3 voltage regulator chip. With the regulator chip, we can have a steady voltage supply to other parts of our circuit.

Requirement	Verification
Stable 3.3V ± 0.3V is supplied to the data transmission module and signal amplification module	1. Connect a voltmeter to VCC and GND of the control unit and amplification unit 2. Check whether stable voltages are supplied to two units.

Table 1. RV Table for Power Module

2.3.2 Skin Patch Module

The device is big enough to hold the necessary components, such as the power supply and circuit board, and small enough to carry in an emergency situation. ECG electrode patches, which are already commercially available, will be used to ensure adhesion between the device and the skin.

Requirement	Verification
Skin patches should be attached to the skin along with the device for at least 5 minutes.	1. Install the patches on the body while the person is at rest and standing. 2. Check, with a timer, whether the device stays on the body for 5 minutes. 3. Check, with a timer, whether the device stays on the body for 5 minutes when the person is walking at a steady pace of 3 mph.
Skin patches should be replaceable without causing damages to the device.	1. Install the patches on the device 2. Remove the patches. 3. Repeat steps 1-2 for 50 times, check whether the device is still able to produce an ECG waveform on monitor
The temperature of patches should be at most 35℃ during operation.	1. Use a thermometer to check the temperature of patches for at least 5 minutes.

Table 2. RV Table for Skin Patch Module

2.3.3 Signal Amplification and Filtering Module

For a typical EKG, the voltage reading ranges from 0.1mV to 10mV in both positive and negative directions, depending on the direction of the depolarization wave. In order to have these readings digitally, an amplifier should be designed. The amplifier

will take the signal from the electrode and amplify this signal by a factor of 150. Then the signal goes through voltage biasing such that all voltage values are positive. This is because ADC can only read positive voltage measurements.

For the amplifier and the filter, we will choose AD8232 by Analog Device. The AD8232 allows us to amplify the input signal and implement both high-pass and low-pass filters to get the desired cutoff frequency from 1Hz to 30Hz. From the datasheet, we also see that AD8232 is designed to amplify and filter the signal in the presence of noisy environments like those created by motion or remote electrode placement. This advantage perfectly meets our requirement for this part design.

Requirement	Verification
The analog amplifier should amplify the signal by a factor of at least 150 for the input range of -1mV to 1mV.	1. Connect the amplifier input voltage to an oscilloscope and measure five voltage measurements of the waveform 2. Connect the amplifier output voltage and repeat step 1. 3. Calculate the gain by taking the ratio of measured output voltages and input voltages 4. Check whether the ratio is within 10% of the desired gain.
The amplifier should amplify the signal at most to a value such that its maximum does not exceed the maximum value of the input of ADC.	1. Connect the amplifier input voltage to an oscilloscope and measure the maximum voltage of the waveform 2. Compare and verify that this value is smaller than the maximum input voltage of ADC.

The filter should attenuate frequencies other than [1Hz, 30Hz] for at least 10dB.	1. Use a VNA and use probes to connect two measurement ports to the input and output of the filter module.
	2. Measure attenuation amount in dB at 1Hz and 30Hz and verify that it is more than 10dB.

Table 3. RV Table for Signal Amplification and Filtering Module

2.3.4 Data Transmission Module

The data transmission subsystem is responsible for sending the digital signals collected from 4 electrodes to the data visualization module and calculating a dataset for 3 leads each, using the Bluetooth module of the microcontroller. This module transmits the data from the hub where all the measurements are collected to the computer/phone. The data of leads are calculated before the transmission as follows:

$$Lead\ I\ =\ LA\ -\ RA \qquad [6]$$
$$Lead\ II\ =\ LL\ -\ RA \qquad [6]$$
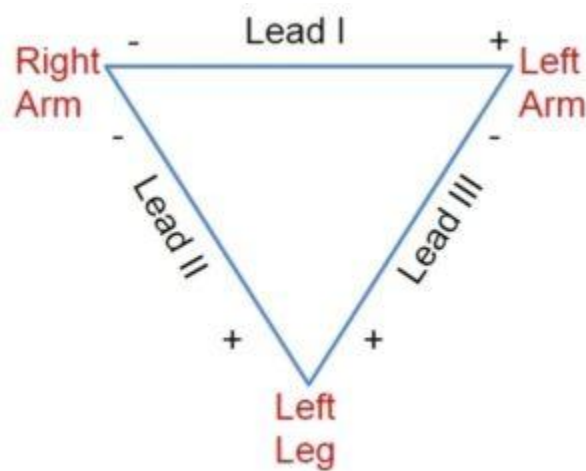$$Lead\ III\ =\ LL\ -\ LA\ =\ Lead\ II\ -\ Lead\ 1 \qquad [6]$$

Figure 10. Diagram of relationship between LL, RA, LA electrodes and Lead I, II, III. Adapted from [7].

Lead 1 and Lead 2 will be calculated in this module before the data transmission, and the calculated data points will be transmitted to the computer/phone. Lead 3 will be calculated in the data visualization module, using the received data, Lead 1 and Lead 2. We need at least an 18 Kbps transmission rate to transmit these two data sets, and the computation is as follows:

The computation is based on the formula,

$$Frequency \times bit\ depth \times channels\ =\ bit\ rate\ \text{[8]}.$$

ESP32's analog input pins have 12-bit resolution [9]. The horizontal size of the smallest grid on the ECG graph that will be visualized is 0.04 seconds. We want at least 10 measurements to be presented per grid. Each measurement needs 1 data point for the measurement value, 1 data point to indicate which lead the measurements are for, and 1 last data point for the timestamp that the signal is measured at. Therefore, our model desires

$$(10\ measurements) \cdot (3\ data\ points/measurement)/0.04\ seconds$$
$$= 750\ points/second$$

Since each point is 12 bits, we need

$$12\ bits/point \cdot 750\ points/second = 9000\ bits\ per\ second.$$

This means we need 9000 bits per second for one lead. We send data points for two leads and calculate the last lead data after the data transmission. The module sends data points for two leads, so we need

$$9000\ bits/second/lead\ \cdot 2\ leads = 18000\ bits\ per\ second.$$

Therefore, we require an 18 Kbps or higher transmission rate.

In addition to the transmission rate, we also restrict delay in transmission to within 10 seconds in 5m distance between the hub and a computer/phone without any barriers in between. The microcontroller that we are planning to use (ESP 32) has a Bluetooth module with a maximum of 4 Mbps [9], which satisfies our design requirements. However, its transmission rate may vary depending on the actual application environment and will require tests.

Requirement	Verification
The module should successfully transmit the data from the hub to the computer/phone, using the Bluetooth module of the microcontroller.	1. Send a set of sample data points from the hub to the computer/phone, using the data transmission module 2. Record the data points sent 3. Record the data points received at the data visualization module 4. Compare the data points sent from the hub and data points received at the computer/phone 3. Verify if all the data points sent are received (either by manually checking or by running a piece of code that does the verification on the data visualization module)
The module should transmit the data at 18 Kbps or higher frequency.	1. Calculate the data transmission rate (data transferred / duration) [10] (either by manually checking or by running a piece of code that does the verification on the data visualization module) 2. Verify if the calculated data transmission rate is at least 18 Kbps
The module should deliver the data from the hub to the computer/phone within 10 seconds in 5m distance between the hub and computer/phone without any barriers in between.	1. Place the data transmission module (hub) and the data visualization model (computer/phone) 5m apart 2. Send a set of sample data points from the hub to the computer/phone 3. Record the timestamp when sending the data (either by manually recording it or by running a piece of code) 4. Record the timestamp when receiving the data (either by manually recording it or by running a piece of code) 5. Compare the timestamps 6. Verify if the difference between two timestamps is within 10 seconds

Table 4. RV Table for Data Transmission Module

2.3.5 Data Visualization Module

The data visualization module is responsible for displaying the ECG signals. The module is divided into two parts: data processing and data visualization. The data processing part receives the data from the data transmission module, using a computer's/phone's built-in Bluetooth module, and calculates any necessary computations to visualize the data, including Lead 3 ($= Lead\ 2 - Lead\ 1$) computation. Then, the received data and calculated data will be transformed into a form that can be graphed (voltage vs. time).

The data visualization part shows the prepared data of each lead with its label. In our design, it will show 3 graphs (Lead 1, Lead 2, and Lead 3). The graphs will be shown in UI either on a computer or phone, depending on the time frame. If we are creating a website to display on a computer or monitor, we will use Chart.js, which is an open-source JavaScript library for data visualization. If we are creating a phone app to display on a phone, we will use React Native, which is an open-source UI software framework. The refreshing rate time interval for graph displays will be at least 4 milliseconds because we aim to display 10 points in 0.04 seconds $(0.04\ seconds/10\ points = 0.004\ seconds\ per\ point)$ as described in the data transmission subsystem.

Requirement	Verification
This module should successfully display 3 graphs (Lead 1, Lead 2, and Lead 3).	1. Verify if 3 graphs are displayed on a computer/phone by counting how many graphs are visually present on the computer/phone screen

Table 5. RV Table for Data Visualization Module

2.4 Tolerance Analysis

The most critical aspect of our project's performance is data transmission. The minimum required transmission rate of Bluetooth modules is subject to change based on how we transmit the data, how many Bluetooth modules we use (whether we use one for both ADCs or one for each ADC), and how many datasets we send per data transmission. The current design we are planning to use is to use two Bluetooth modules (one per data transmission) and send only one data set for each data transmission. Therefore, the minimum transmission rate is calculated by formula

$$bit\ rate\ =\ Frequency \times bit\ depth \times channels\ \ [8]$$

and the computation for our design is as follows:

ESP32's analog input pins have 12-bit resolution [9], which is the bit depth in this case. The unit of the time axis on the ECG graph is 0.04 seconds, and we want at least 10 points in one unit. Each point needs 1 datum for voltage measurement, 1 datum to indicate which lead the measurements are for (among the two), and 1 last datum for the timestamp that the signal is measured at. Therefore, our model desires

$$(10\ measurements) \cdot (3\ data\ points/measurement)/0.04\ seconds$$
$$=\ 750\ points/second$$

Since each datum is 12 bits, we need

$$12\ bits/point \cdot 750\ points/second = 9000\ bits\ per\ second.$$

This means we need 9000 bits per second for one lead. We send data points for two leads and calculate the last lead data after the data transmission, so we do not send data for lead 3. The module sends data points for two leads, so we need

$$9000\ bits/second/lead\ \cdot 2\ leads = 18000\ bits\ per\ second.$$

Therefore, our design requires an 18 Kbps or higher transmission rate.

However, the minimum required transmission rate can change, depending on how many data sets we would like to send at a time. For example, if we use only one Bluetooth module to send the data, and we want to send N sequential sets of data for

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two leads to have N points in one unit (N sets of data for lead 1 and another N sets of data for lead 2) at one data transmission, we need a higher transmission rate:

The bit depth remains as 12-bit. We want N points in one unit. As our current design, each point needs 3 data points (1 for voltage measurement, 1 for lead indication, and 1 for timestamp). Therefore, our model desires

$$(2N \; measurements) \cdot (3 \; data \; points/measurement)/0.04 \; seconds$$
$$= 150N \; points/second$$

Since each datum is 12 bits, we need

$$12 \; bits/point \cdot 150N \; points/second = 1800N \; bits \; per \; second.$$

This means we need 1800N bits per second for both leads. Therefore, based on the number of datasets we send per transmission, the minimum transmission rate can change.

In addition, depending on what microcontroller we use and how we send the data (not just about the number of data sets but the algorithm), which is subject to change as the project progresses, the required transmission rate can be higher or lower than the transmission rate of the previous example or current design.

3. Cost and Schedule

3.1 Cost Analysis

Assuming hourly rate for an Electrical Engineering student is $50/hr and each team member will work 8 hours per week. We estimate that we will be working around 10 weeks, so the total estimate is the following:

$$\$50/hr \cdot 8hr/week \cdot 10\,weeks \cdot 3members = \$12000$$

For labor, including the overhead cost, it becomes

$$\$12000 * 2.5 = \$30000$$

Besides, we also have to consider costs on our parts:

Name	Quantity	Price
AD8232 (Amplifier & Filter)	2	$3.26
3.3V Voltage Regulator (LM1117)	2	$1.52
9V battery	2	$7.99
ECG electrode patches	1 (Bag of 100)	$17.62
ECG compatible Leadwire	2 (each with 3 wires)	$34.00
Retractable Wire	1 (Pack of 3)	$8.69
ESP32	1	$6.5
Total:	11	$79.54

Table 6. Cost Analysis Table

3.2 Schedule

Week	Halim	Ye	Juhyeon
2/21	Design Review	Design Review	Design Review
2/28	Finalize design detail & Order design-related components	Finalize design detail & Order circuit-related parts	Finalize design detail & Order circuit-related parts
3/7	PCB Design	PCB Design	PCB Design
3/14	Break		
3/21	Solder PCB	Solder PCB	Solder PCB
3/28	Test Filter Subsystem	Test Amplification Subsystem	Start working on Data Transmission Subsystem and Visualization Subsystem, using sample data
4/4	Test Filter & Amplification Subsystem	Test Filter & Amplification Subsystem	Test Data Transmission Subsystem and Data Visualization Subsystem with data of our design
4/11	Whole system test	Whole system test	Whole system test
4/18	Prepare for demo	Prepare for demo	Prepare for demo
4/25	Final presentation	Final presentation	Final presentation
5/2	Final report	Final report	Final report

Table 7. Schedule Table

4. Ethics and Safety

Section 1.1 of ACM code wants people to use their skill to benefit society, its members, and the environment surrounding them [12]. We believe that our design is a step towards the final creation, which will benefit all people suffering from heart disease and other diseases which can be monitored in our device.

Since our devices are directly attached to the people's skin, we ensure the stability of our circuits and control the temperature of each patch to be acceptable for the human body. Also, we will check all our parts to make sure that they are not broken and stay in good status for work. These meet the requirement of section 1.2 of ACM code, which requires devices to minimize negative effects on people [12].

Besides, we also consider section 1.7 of ACM code, which ensures us to maintain user confidentiality [12]. We know that personal privacy is one of the most important concerns for patients, so we promise that we would not collect users' health information for trade, business, and all other unethical purposes.

In this project, we are trying to reduce the number of wires used and have some other changes to make it more convenient and replicable for practical applications. We believe that these improvements can be innovative and beneficial for future uses to help more patients with heart diseases. This is also what section 1.5 of ACM code hopes us to achieve in our final design [12].

5. Citations

[1] TUCCI KINESIOLOGY. 2022. *ECG*. [online] Available:

<http://tuccikinesiology.weebly.com/ecg.html>

[2] Apple Support. 2022. *Take an ECG with the ECG app on Apple Watch*. [online] Available at:

<https://support.apple.com/en-us/HT208955>

[3] Irhythmtech.com. 2022. *Zio Monitoring*. [online] Available:

<https://www.irhythmtech.com/providers/zio-service/zio-monitors>

[4] BardyDx. 2022. *CAM Patch*. [online] Available: <https://www.bardydx.com/solutions/cam/>

[5] "Retractable Car-Stereo Cable | Belkin", *Belkin*, 2022. [Online]. Available:

https://www.belkin.com/us/cables/audio/retractable-car-stereo-cable/p/p-f3x1980-rtc/.

[6] M.S. Thaler, *The Only EKG Book You'll Ever Need*, 5th ed. Philadelphia, PA, USA: Lippincott
Williams & Wilkins, 2007.

[7] "TWELVE LEAD ECG", ALL ABOUT CARDIOVASCULAR SYSTEM AND DISORDERS,
2022. [Online]. Available:

https://johnsonfrancis.org/professional/ecg-basics-a-brief-review/twelve-lead-ecg/. [Accessed:
24- Feb- 2022].

[8] "Encoding Audio and Video", *Bitesize*. [Online]. Available:

https://www.bbc.co.uk/bitesize/guides/z7vc7ty/revision/4

[9] Espressif Systems, Shanghai, China. *ESP32 Series Datasheet*, v3.8 (2021). Accessed:
February 21, 2022. [Online]. Available:

https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

[10] S. Wooding, 'Data Transfer Calculator', 2021. [Online] Available:

https://www.omnicalculator.com/other/data-transfer#:~:text=The%20formula%20to%20calculate
%20the,speed%20%3D%20data%20transferred%20%2F%20duration

[11] "Chapter 14: ADC, Data Acquisition and Control", Users.ece.utexas.edu, 2022. [Online].
Available:

https://users.ece.utexas.edu/~valvano/Volume1/E-Book/C14_ADCdataAcquisition.htm

[12] "ACM Code of Ethics and Professional Conduct", Association for Computing Machinery, 22
June 2018. [Online]. Available: https://www.acm.org/code-of-ethics

[13] "The ECG leads: electrodes, limb leads, chest (precordial) leads, 12-Lead ECG (EKG)", *ECG & ECHO*, 2022. [Online]. Available:

https://ecgwaves.com/topic/ekg-ecg-leads-electrodes-systems-limb-chest-precordial/#:~:text=The%20standard%20ECG%20%E2%80%93%20which%20is,referred%20to%20as%20precordial%20leads.

[14] "Electrocardiogram", *Mayo Clinic*, 09 April 2020. [Online].

Available: https://www.mayoclinic.org/tests-procedures/ekg/about/pac-20384983

[15] C.Abreu-Lima, J.P.Marques, G.Coelho, J.Almeida, F.Silva-Carvalho, and C.Hernandez. (1988, Nov). *Frontal-plane QRS axis revisited: accuracy of current approximations and reappraisal of their merit in the diagnosis of right ventricular hypertrophy* [Online]. Available:

https://pubmed.ncbi.nlm.nih.gov/2977149/#:~:text=The%20frontal%2Dplane%20mean%20QRS,deflections%20in%20two%20different%20leads.

[16] Cables and Sensors. (N.d.). *12-Lead ECG Placement Guide with Illustrations* [Online]. Available:

https://www.cablesandsensors.com/pages/12-lead-ecg-placement-guide-with-illustrations

[17] R.Brock. (2020, 04). *Why is my screen black?* Available:

https://www.kdab.com/why-is-my-screen-black/

[18] R.E.Klabunde. (2019, Nov 18). *Electrocardiogram (EKG, ECG)* [Online]. Available:

https://www.cvphysiology.com/Arrhythmias/A009

[19] L.G.Tereshchenko. (2016, Nov 01). *Frequency Content and Characteristics of Ventricular Conduction* [Online]. Available:

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4624499/

[20] "ESP32 Analog Input with Arduino IDE", *Random Nerd Tutorials*, 31 May 2019. [Online]. Available: https://randomnerdtutorials.com/esp32-adc-analog-read-arduino-ide/

[21] S. Meek and F. Morris, "Introduction. I–Leads, rate, rhythm, and cardiac axis," *BMJ Publishing Group*, Vol. 324, No. 7334, 16 February 2022. Available:

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1122339/#:~:text=To%20assess%20the%20cardiac%20rhythm,to%20record%20the%20rhythm%20strip.