Wireless ECG

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Final Report for ECE 445, Senior Design, Spring 2022

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5 May 2022

Project No. 9

Abstract

The main purpose of this project is to provide a solution to patients with heart-related symptoms and doctors to monitor and diagnose heart health. Our solution becomes more explicitly effective in emergency situations as time is the most crucial factor.

Our project focuses on creating a portable ECG (Electrocardiogram) with wireless implementation, which can provide a 3D view of the heart and hence assist with diagnosis of heart-related symptoms. Its wireless feature eliminates the issue of tangling wires involved in a traditional 12-lead ECG.

The result of the project is a 3-lead wireless ECG that serves as a starting point for the ultimate goal of creating a 12-lead ECG. A central hub of the device can be attached to the body and it transmits the analyzed heart signal data wirelessly through bluetooth. Received data can be displayed on the monitor to visualize the ECG graphs.

Contents

1. Introduction

Cardiovascular diseases (CVDs) are the main causes of death globally. According to WHO, CVDs represent 32% of all global deaths, having approximately 17.9 million deaths from CVDs in 2019. [1] While most CVDs can be prevented by controlling risk factors such as diet, tobacco use, etc. , it is more important to be able to detect CVDs beforehand.

Electrocardiogram (ECG) is one of the simplest and quickest diagnosis tools to evaluate the heart. Electrode patches are placed at certain parts of the body surface, and the electrical activity of the heart can be measured and visualized. An ECG detects changes in the biopotential of the body surface, primarily driven by contractions of the different parts of the heart. It can detect the interval rhythm, amplitude, and timing of these electrical impulses, and any abnormalities in them can be indicators of heart-related conditions.

In a traditional 12-lead ECG, 10 electrodes are placed across the body, which are necessary to provide a 3D view of the heart for accurate analysis. The problem emerging from it is that there needs to be 10 separate wires all connected to a detection device that is usually placed a distance away from the body.

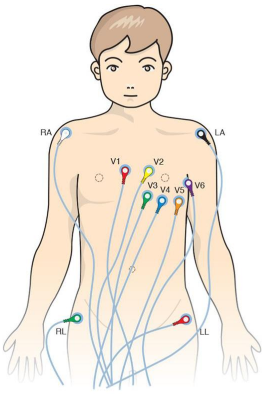


Figure 1. Location of electrode placements in a traditional 12-lead ECG. Adapted from [2]

Many of us have experienced the old era when we used wired earphones to listen to music. Earphone wires can get so knotted in such a short time, and even a research paper is established to explain the theory behind it [3]. As opposed to 2 wires in earphones, 10 wires in a traditional ECG would be worse. Tangling wires prevent users from attaching electrodes in a quick manner, which dramatically degrades convenience. In emergency situations, this can lead to untimely diagnosis and even death.

Now that the issue of tangling earphone wires is resolved with the invention of wireless earbuds, our group felt it necessary to create a wireless ECG that minimizes electrode wire involvement. We have designed a wireless 3-lead ECG that minimizes the number of wires involved compared to a 12-lead ECG. It only requires three wire attachments and three of them are grouped into a retractable cable system to minimize any tangling wire issue. The main hub can be attached on the body and has a wireless capability to transmit the measured signal to the monitor device through bluetooth protocol.

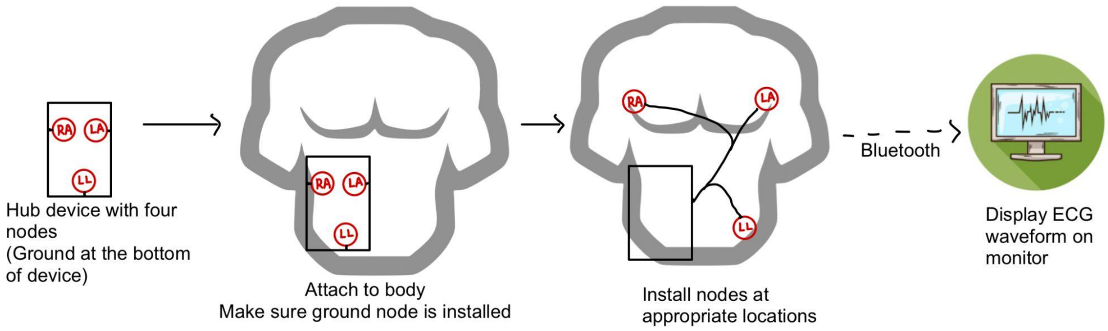


Figure 2. High-level visual representation of the device usage

Our 3-lead ECG device would require 4 electrode placements on the body. However, only 3 wires are required as the main device will be attached above one of the 4 required locations (Right Leg, or RL) and the bottom of the device has an electrode installed on it. The 3-lead graph is displayed after receiving the wirelessly transmitted data from the central hub of the device and can be used for heart diagnosis.

The device includes a rocker switch and an LED indicator, and the LED turns on when the switch is turned on. A user can simply turn the device off when not in operation and power usage is hence minimized. Turning the device on also turns the microprocessor on, which is ready for bluetooth pairing to transmit the heart signal data.

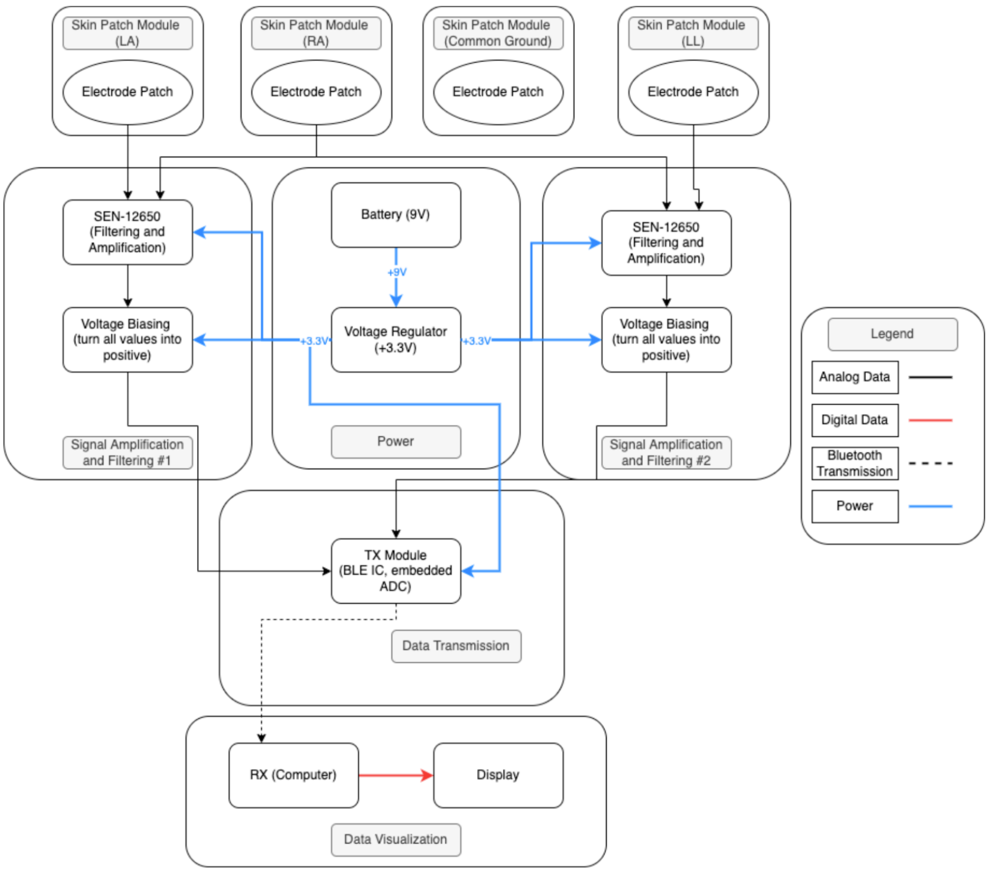


Figure 3. Block Diagram of the wireless ECG device

This device is divided into five main subsystems:

The **skin patch subsystem** is the system that ensures correct electrode measurements and enhanced replaceability. It first needs to sufficiently stick to the body surface to minimize noise introduced from loose connection to the body. Secondly, ECG patches should be replaceable such that the device can be reused multiple times and also on multiple patients by simply replacing the ECG patches. Lastly, the retractable cable system is implemented in a way that minimizes the probability of tangling wires.

The **power subsystem** is the system that provides constant power to our hub device, which includes the signal amplification, filtering, and data transmission subsystem. It is composed of a 9V LiPo battery that can be easily replaced when it runs out, and a 3.3V voltage regulator that provides input voltage of 3.3V to the system with very small ripple. Minimizing the ripple is essential since small ripples can introduce noise to the obtained heart signal.

The **signal amplification and filtering subsystem** is the system that takes the electrode voltage measurements, amplifies and filters them to produce the resulting output signal. It takes voltage measurements from four electrodes: Right Arm (RA), Left Arm (LA), Right Leg(RL), Left Leg(LL). RA, LA, LL are used to obtain the 3 leads, and RL is used as a reference node to cancel out noise components emerging from the body.

The **data transmission subsystem** is the system that preprocesses the amplified and filtered data fed into the microcontroller for the purpose of distinguishing the Lead 1 from Lead 3 data and vice versa. Then, It sends the data to the data visualization subsystem, using the Bluetooth Low Energy (BLE) module of the microcontroller.

The **data visualization subsystem** is the system where three graphs of the data of three leads are displayed. It receives the data from the data transmission subsystem and visualizes the data in real-time. It is where Lead 2 data are calculated and displayed along with Lead 1 and Lead 3 graphs.

2. Design Procedures

2.1 Skin Patch Subsystem

2.1.1 Adhesive ECG patches

One of the requirements for our wireless ECG is that the device, while big enough to hold necessary components, should be compact in size and light in weight such that it can be attached on to one's body without falling off. ECG electrode patches, which are already commercially available, are used to ensure adhesion between the device and the skin. It was decided that two skin patches should be mounted on the bottom of the device, of which one is for the Right Leg electrode measurement, and another one is solely for adhesion purposes. Instead of placing a single circle-shaped patch, two square-shaped patches are implemented to accommodate as much surface area as possible for adhesion while preventing the patches from sticking together.

$$A_{circle\ patch} = \pi(\frac{5.1cm}{2})^2 = 20.43cm^2,\ A_{square\ patch} = 2 * 3.8cm * 4.3cm = 32.68cm^2$$

The ECG electrodes were chosen considering their durability and mountability onto our enclosure, such that our device is able to measure and produce ECG signals even after multiple patch replacements.

Figure 4. 3M 2650 multi-purpose monitoring ECG patches (right) and patches on the bottom of the device (left)

2.1.2 Retractable Wire System

Since our design involves a central hub located on the Right Leg (RL) part of the body, there is some inevitable wire usage to connect the other electrodes (RA, LA, LL). In order to minimize the wire tangling issue as we have described in the introduction, a DIY retractable wire system is implemented. It is inspired by a 3.5mm earphone retractable cable in the market. Upon numerous trials and errors, we were able to take an existing retractable cable system apart and replace it with our ECG wire. It can be pulled to different lengths and the system would hold that length. The spring mechanism within the system allows one to simply pull the cable slightly and would retract back into its original state. The ability to be fixed to different lengths ensures minimum wire involvement covering patients with different body sizes. It can be extended to a maximum of 3 feet, which is sufficient enough to cover the upper body of patients. Figure below shows a comparison of this system fixed in different lengths:

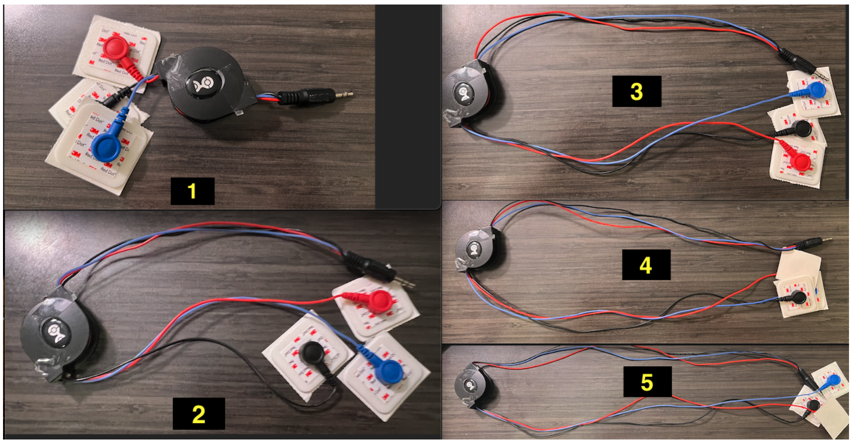


Figure 5. Our DIY retractable wire system fixed at different lengths, <1> at the minimum length and <5> at the maximum length

The other end of the wire is a 3.5mm audiojack, and the three electrode signals are guided to the tip, ring, and sleeve of the audiojack (and onto the PCB):

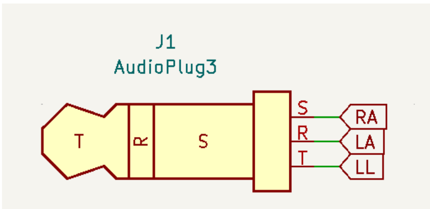


Figure 6. Schematic of the skin patch module

2.2 Power Subsystem

2.2.1 Power Supply

For the whole system, we need to supply a stable 3.3V voltage to both signal amplification module (AD8232) and data transmission module (ESP32). Therefore, we used a 9V battery to supply the power and two LM1117-3.3V voltage regulators to provide a stable +3.3V for the amplifier, biasing circuit, ADC, and BLE ICs.

2.2.1 Design Detail

The battery was attached at the bottom of the central hub, which is easily replaceable. Also, we inserted a rocker switch outside the hub, so we could easily control the power supply status.

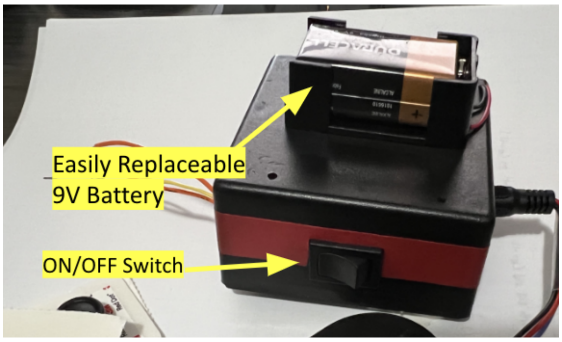


Figure 7. Power supply and the switch control

The switch is placed in the middle of the battery and the voltage regulator, such that the main voltage course is completely disconnected when not in use and hence minimizes idle power consumption.

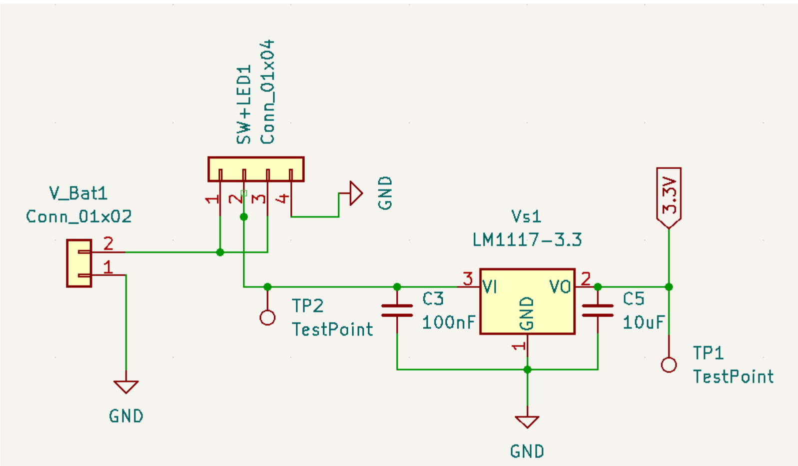


Figure 8. Schematic of the power subsystem

2.3 Signal Amplification and Filtering Subsystem

For a typical ECG, 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 is designed for higher resolution. It is also important to not exceed the maximum input voltage of the ADC, which is 3.3V.

For the amplifier and the filter, we have chosen AD8232 by Analog Device. The AD8232 chip allowed 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 met our requirement for this part design. With the correct biasing of this chip with lumped components, we were able to achieve amplification, filtering, and voltage biasing all together. Refer to Appendix C for the recommended biasing circuit provided by the AD8232 datasheet [4].

Obtaining a 3-lead measurement would require 3 such chips, but we were able to reduce them down to 2 using the concept of Einthoven's Triangle, such that lead II measurement can be obtained by the sum of lead I and III signals. This was important since minimizing the size of the device is a crucial factor to users' convenience.

$$Lead\ I = LA - RA \quad [5]$$

$$Lead\ III = LL - LA \quad [5]$$

$$Lead\ II = LL - RA = Lead\ I + Lead\ III \quad [5]$$

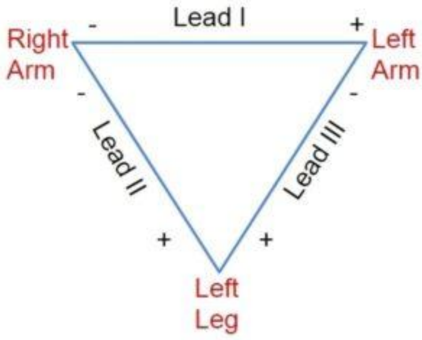


Figure 9. Diagram of relationship between LL, RA, LA electrodes and Lead I, II, III. Adapted from [5]

Lead I and III are measured and the output heart signal is fed into the data transmission and visualization subsystem. Lead III is calculated digitally and displayed in the data visualization system. As a result, one less chip and one less input to the microprocessor are required, contributing to a compact device size and less power usage leading to longer battery life.

The schematic with the configuration is as follows:

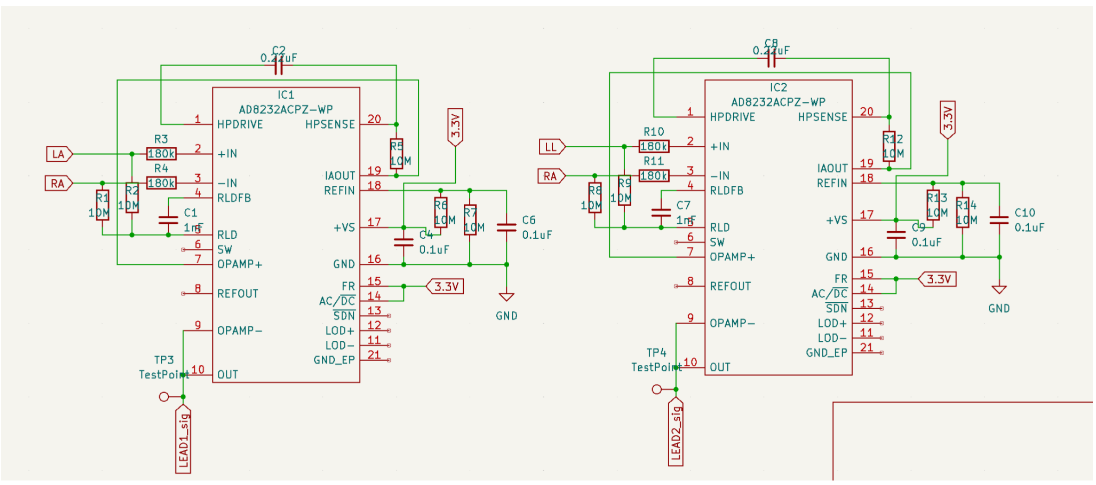


Figure 10. Schematic of the configuration circuit of AD8232

2.4 Data Transmission Subsystem

The most significant software part of the product is to wirelessly transfer data to the data visualization subsystem. There are two requirements for successful data transmission: acquiring a transmission rate minimum of the required transmission rate and preprocessing data before sending the data to the data visualization subsystem.

2.4.1 Data Transmission Rate

The required data transmission rate is subject to change based on the specific implementation of data transmission. The followings are what the updated minimum data transmission rate is and how it is achieved in the project:

The transmission rate required is obtained as the following formula:

$$bit\ rate\ = Frequency \times bit\ depth \times channels$$ [6].

Each graph displays 10 data points per 0.04 seconds.

$$(10\ points)\ /\ 0.04\ seconds =\ 250\ points/second$$

Since each data point is sent as 2 bytes, we need

$$2\ bytes/point\ \cdot\ 8\ bits\ /\ byte\ \ \cdot\ 250\ points/second\ =\ 4000\ bits\ per\ second\ .$$

This means that 4000 bits per second should be transferred to the data visualization module for one lead. Lead 1 and Lead 3 data points are sent, and Lead 2 data is calculated in the data visualization module, which will not be transferred wirelessly. Therefore, there are two leads whose data need to be wirelessly transferred.

$$4000\ bits/second/lead\ \ \cdot\ 2\ leads\ =\ 8000\ bits\ per\ second.$$

Therefore, we require 8 Kbps or higher transmission rate.

2.4.2 Preprocessing Data

The way the data receiver distinguishes the Lead 1 and Lead 3 data from each other is by using the most significant bit (MSB). Since the data transmission module sends each (filtered and amplified) measurement as 2-byte data, the 16th bit is set to 0 if the data is a Lead 1 measurement. Otherwise, it is set to 1 to indicate that the data is Lead 3. This is possible because it is guaranteed by the Signal Amplification and Filtering Subsystem that the maximum data fed into ESP32 does not exceed $2^{14}\ =\ 16384$, which allows the system to use MSB (the 16th bit) as an indicator of which lead the data is.

Once the Lead 1 and Lead 3 data are received by the data visualization subsystem, Lead 2 is calculated by summing up the Lead 1 and Lead 3 data in the data visualization subsystem.

2.4.3 Data Transfer

The product uses a built-in Bluetooth Low Energy (BLE) module in ESP32. Using the ESP32 BLE module is sufficient and more efficient than using the ESP32 Classic Bluetooth module because the amount of data BLE can handle is sufficient for the project and can maintain longer battery life.

The ESP32 BLE module has a data transmission rate up to 1Mbps [8], which is much greater than our design required (8 Kbps).

2.5 Data Visualization Subsystem

2.5.1 Data Post-processing

Once the data is received, the system extracts the MSB to correctly classify the data into either Lead 1 or Lead 3. The data is classified into Lead 1 if the MSB is 0. Otherwise, it is classified into Lead 3. APPENDIX B-1 shows the two files of classified data.

Lead 2 data is calculated by summing up Lead 1 and Lead 3.

2.5.1 Data Visualization

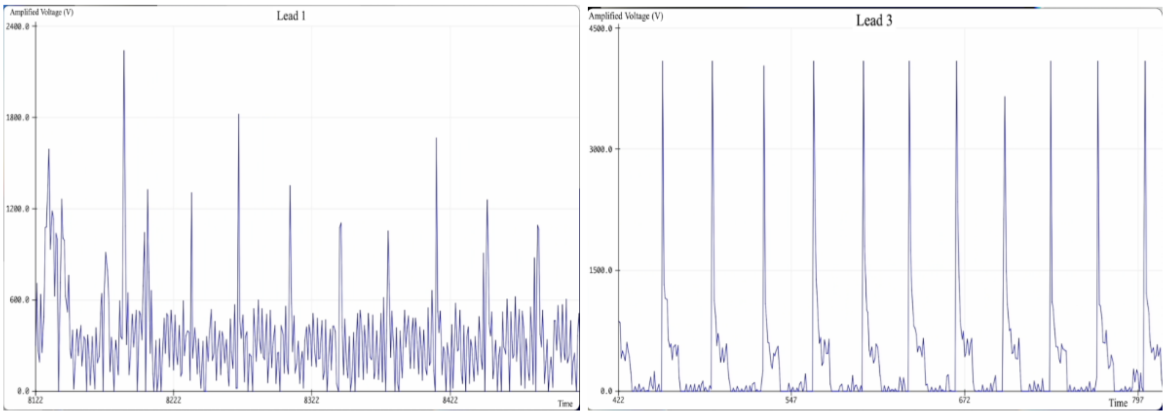


Figure 11. Graphs of Lead 1 and Lead 3 Data Received in the Data Visualization Subsystem

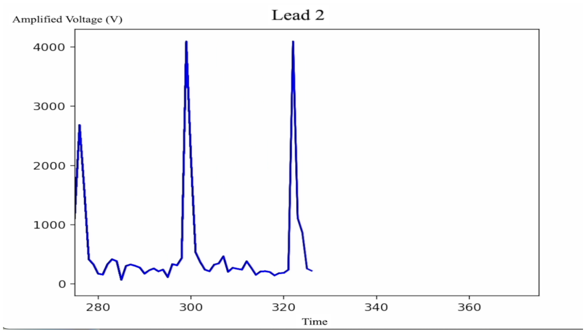


Figure 12. Graph of Lead 2 Data

Figure 11 and Figure 12 show graphs, each representing each lead (Lead 1, Lead 3, and Lead 2). The three graphs are displayed on the computer screen in real-time as the subsystem keeps receiving new data.

2.6 Physical Design

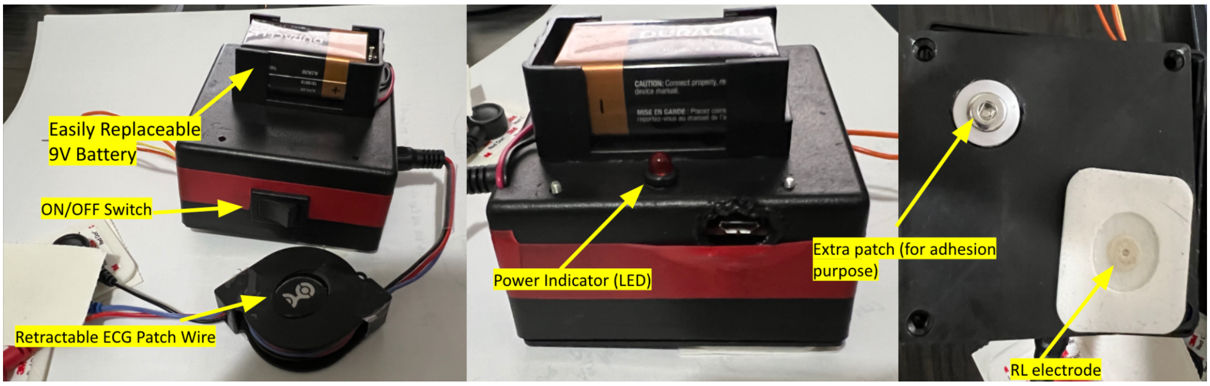


Figure 13. Developed product with its features explained

Above figure shows our developed product with its features. To achieve convenience of usage, a rocker switch and a LED power indicator is mounted to the enclosure so that the power can be turned off when not in use, which a user would be able to tell from the LED. A 9V battery is placed above the device so that it can be easily replaced when the battery runs out.

The main goal when considering the physical design is to minimize wire usage and be compact in size and weight. As described in section 2.1.1, we have achieved minimal wire usage by placing the Right Leg (RL) electrode at the bottom of the device such that there is no wire coming outside of the device for the RL electrode. As described in section 2.1.2, we have successfully implemented the retractable wire system to eliminate the issue of tangling wires when using the device.

We have designed our PCB such that compactness in size is achieved. It has a size of 64.23mm x 74.93mm, which is small enough to be attached onto the body surface.

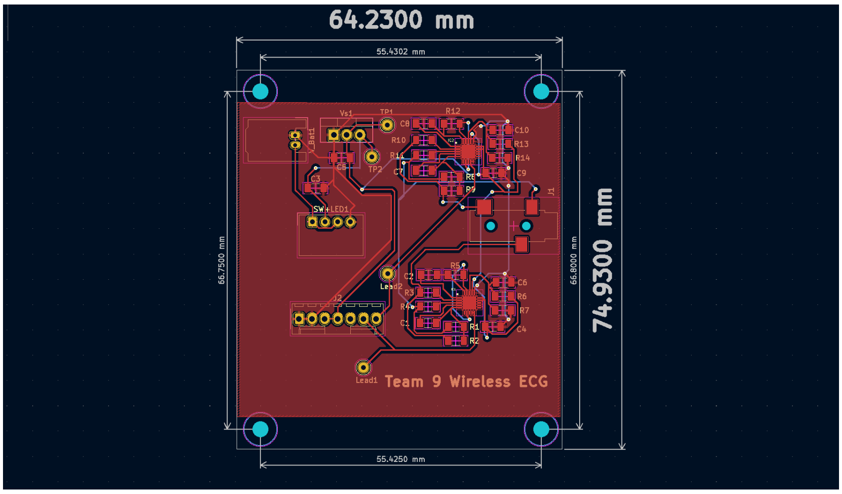


Figure 14. PCB board design with dimensions

3. Design Verification

3.1 Skin Patch Subsystem

Justifications are made in section 2.1 regarding skin patches to ensure reusability and convenience of our design. Verifications included checking correct device functionalities with repeated skin patch installations, long-time usage of the device, and the temperature of the skin patches to ensure the device does not cause any skin irritation. All requirements in the skin patch subsystems all proved to be verified, hence the skin patch subsystem is fully functional.

We checked whether the two ECG patches at the bottom of the device can be attached onto the body while standing still. It was proven that it stays on the body for at least 10 minutes, outperforming our requirement. Furthermore, the electrodes were very durable, so it was able to detect and produce the heart signal even after the patches were installed and removed for at least 50 times. Regarding the temperature, we used a thermometer gun to measure the temperature of the patches when the device is in operation. The thermometer is pointed at the foam part of the ECG patch, which is in direct contact with the body surface. An average is taken from 10 repeated measurements at different electrode patches and they all fall below our requirement of 35˚C (See table below)

Table 1. ECG patch average temperature measurements

	Measurement Electrode				
	Away from the device			At the bottom of the device	
	Right Arm	Left Arm	Left Leg	Right Leg #1	Right Leg #2
Average Temperature (˚C)	29.4	29.8	29.1	31.4	32.0

3.2 Power Subsystem

We used a voltmeter to check the voltage across the voltage regulator and the input voltage to both AD8232 and ESP32 chips to make sure that they all had a stable 3.3V power supply. We checked that the power supply voltage for these three parts were stable and around 3.3V ± 10mV.

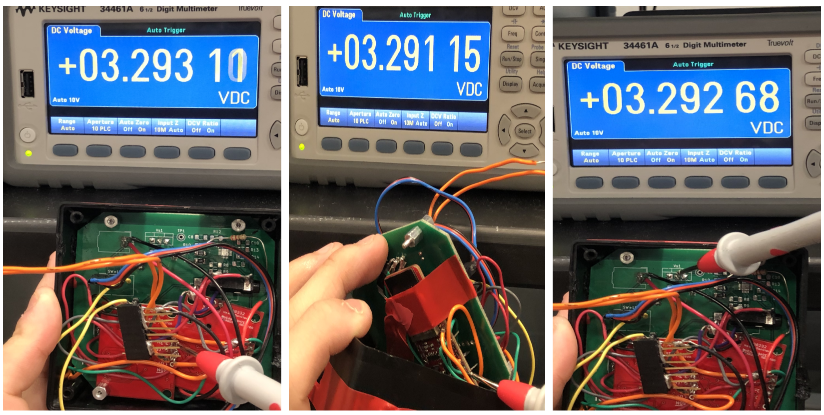


Figure 17. Input voltage for AD8232 (left), ESP32 (middle), and output voltage of the voltage regulator (right)

3.3 Signal Amplification and Filtering Subsystem

3.3.1 Amplification

As mentioned, simply feeding the differential voltage into the ADC would not provide enough resolution since a typical reading has an amplitude of only 10mV. While keeping in mind that the maximum input voltage of the ADC is 3.3V, we have successfully configured the AD8232 chip in a way that it is amplified to a suitable scale. Our requirement was a gain of at least 150, and we have verified that the amplitude of the output signal is around 2.25V.

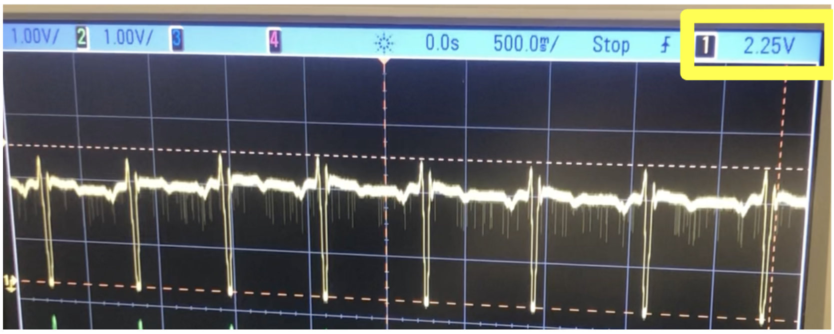


Figure 18. Lead III signal on an oscilloscope. Yellow box shows the maximum amplitude of the signal.

Taking the extreme values of a typical input (10mV):

$$G_{min} = \frac{2.25V}{10mV} = 225$$

It is also important to note that output amplitude of 2.25V provides a safe margin, compared to 3.3V, for the input voltage of ADC. This is further justified by considering irregular heart activities, which can contain spikes with higher amplitude. Therefore, the first two requirements are satisfied.

3.3.2 Filtering

It is essential to filter out any noise components, which are typically outside of [1Hz, 30Hz] range. We set up our requirement that the filter should be able to attenuate frequencies other than that range for at least 10dB. While the output of the signal can be probed with a VNA, we were unable to compare it with the spectrum of the input signal as the filtering system is implemented within the AD8232 configuration. While the steps that we had described for this requirement did not turn out successfully, we can refer to the datasheet of AD8232 for its frequency response [4] (See Appendix C):

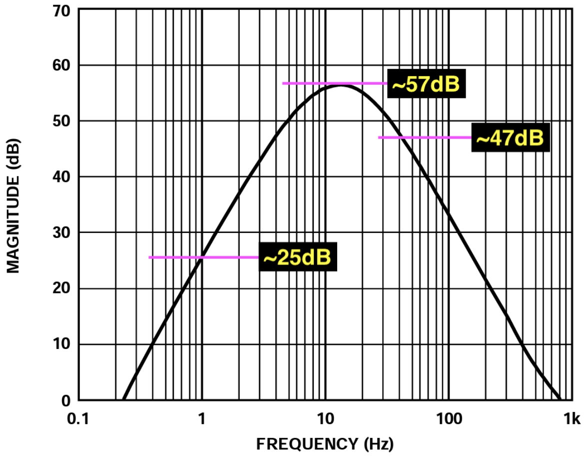


Figure 19. Frequency response of the amplification and filtering provided by AD8232. Adapted from [4]

As we can see from the figure above, there is approximately 22dB attenuation at 1Hz and 10dB attenuation at 40Hz. We can claim partial success of filtering as we were able to produce an ECG signal with little noise and the fact that the datasheet provides a frequency response graph for reference, but they are not sufficient to fully verify our requirement for the filtering portion.

3.4 Data Transmission Subsystem

3.4.1 Data Transfer

APPENDIX B-2 shows that the data are successfully received in the data visualization subsystem by showing a part of the data received. APPENDIX B-2 is the data received from 5m distance away from the computer (the data visualization subsystem), so it verifies that the data transfer can be done from a distance, which gives the user more movement flexibility with the patches attached on the body.

3.4.2 Data Transmission Rate

The minimum transmission rate has changed as the implementation of data transmission became different from the design initially planned to be implemented. The calculation of the new minimum transmission rate is calculated as follows:

Each graph displays 10 data points per 0.04 seconds.

$$(10\ points)\ /\ 0.04\ seconds$$
$$=\ 250\ points/second\ .$$

Each data point is a size of 2 bytes, so we need

$$2\ bytes/point\ \cdot\ 8\ bits\ /\ byte\ \cdot\ 250\ points/second\ =\ 4000\ bits\ per\ second\ .$$

Since we send data of 2 leads (Lead 1 and Lead 3), we need

$$4000\ bits/second/lead\ \cdot\ 2\ leads\ =\ 8000\ bits\ per\ second.$$

Therefore, the new minimum transmission rate required is 8 Kbps.

By limiting the delay (or time sleep) in the code to 4ms for each data transfer of both Lead 1 and Lead 3, the computer receives data at a rate of 8 Kbps.

3.5 Data Visualization Subsystem

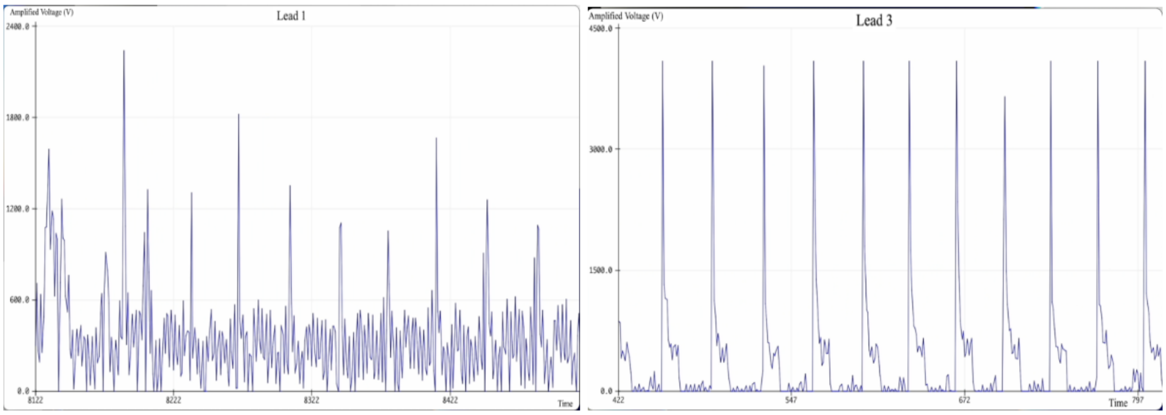


Figure 20. Graph of Lead 1 and Lead 3 Data

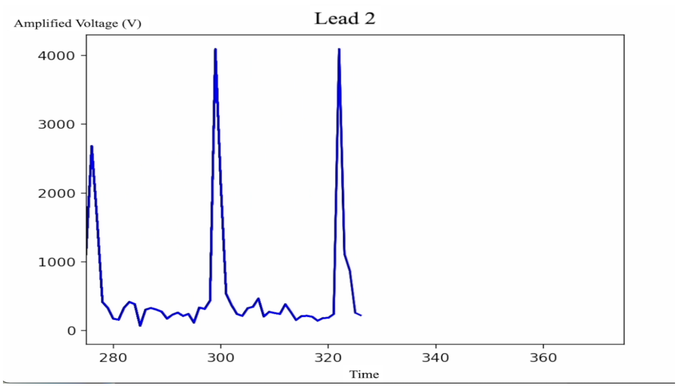


Figure 21. Graph of Lead 2 Data

The subsystem successfully displays three graphs, each representing each lead (Lead 1, Lead 2, and Lead 3), in real-time. Figure 20 shows graphs of Lead 1 and Lead 3 each, which are directly measured by the product. The two displayed graphs look similar to the signals the oscilloscope shows. Figure 21 shows the Lead 2 graph, which is calculated by Lead 1 + Lead 3.

4. Costs

4.1 Parts

Table 2. Parts Costs

Part	Manufacturer	Quantity	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
SparkFun Single Lead Heart Rate Monitor - AD8232	SparkFun	2	21.50	21.50	43.00
Rocker Switch - RA12131100	Mouser	1	0.67	0.67	0.67
TS-3315P Plastic Electronics Enclosure	Polycase	1	4.07	4.07	4.07
MN1604 9V battery	Mouser	3	2.45	2.45	7.35
9V battery snaps	Mouser	1	1.45	1.45	1.45
AD8232 chip	Analog Device	10	4.58	4.12	41.20
3.3V voltage regulator	SparkFun	5	2.10	2.10	10.50
CAB-12970	Digi-Key	2	4.95	4.95	9.90
SJ-3523 Audio Jack	Mouser	2	0.86	0.86	1.72
2mm Pin to 3.5mm Snap Lead Wire Adapters	Tens	1	7.95	7.95	7.95
Retractable Ethernet Cable	Cable Matters	1	9.99	9.99	9.99
				Total Cost	**137.80**

4.2 Labor

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:

$$\$50/hr \cdot 8hr/week \cdot 12\,weeks \cdot 3members = \$14400$$

For labor, including the overhead cost, it becomes

$$\$14400 * 2.5 = \$36000$$

4.3 Schedule

Table 3. Schedule of the semester

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

5. Conclusion

Over the course of the semester, we faced many challenges and learned much when overcoming them. Upon designing subsystems, we learned to combine them in both hardware and software. Many parts required to come up with alternate solutions to satisfy connection with the others. We learned different ways of soldering to make sure that the small chips can work well. Also, we learned how to combine both software and hardware in our design so that we can display the output signals to others. For the group work, we knew how to communicate with each other to work more efficiently, and tried to manage our time to make sure that we would not fall behind the schedule. All these are valuable lessons, and we will benefit from them for future study.

5.1 Accomplishments

Our developed product was able to successfully measure and display Lead I and Lead III signals, and after transmitting the data through bluetooth, display the Lead II signal using the summation of the two. Also, we can use the ESP32 chip to convert the analog input into the digital output so that we can read them on the computer monitor. After receiving the digital data, we can transmit the data to a mobile device by using Bluetooth and plot these data into the graph. By doing this, the signals are visualized.

5.2 Uncertainties

Our current design ensures the device's functionality, but is not the best one. First of all, the bluetooth protocol used in our wireless transmission has a limited effective distance, so the receiver module needs to be placed fairly close to the device. Wifi, for instance, can be used to enable wireless transmission in a longer range. With wifi, we can imagine a remote diagnosis scenario where the doctor is sitting in his office, providing heart signal analysis when a patient has the device installed at home.

The configuration of the circuit with AD8232 chip can be improved to provide higher resolution. Our current maximum amplitude is approximately 2.25V, which is good enough considering the fact that the maximum input voltage of the ADC is 3.3V. However, we would be able to produce a much clearer signal if the gain is adjusted higher than what we have now, to have a maximum amplitude of approximately 3.2V.

Though we were able to produce the ECG signals, it was hard to objectively compare them with the traditional 12-lead ECG signals. Yet it was clear that digital outputs on the computer contain noise components. In figure 1829, we can see a thick line between the spikes. When stretched horizontally, we were able to see a constant noise component at around 50Hz that contributed to such a result. This would require noise filtering algorithms in the digital domain to be accounted for. A traditional ECG would be required to claim accuracy of our produced signals.

With these changes, functions of the device will be improved, and the device will have better competition in the market.

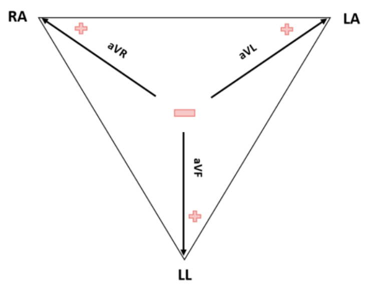
5.3 Ethical considerations

Section 1.1 of ACM code wants people to use their skill to benefit society, its members, and the environment surrounding them [8]. 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 device is directly attached to the people's skin, we ensured the stability of our circuits and controlled the temperature of each patch to be acceptable for the human body. Also, we checked all our parts to make sure that they were not broken and stayed 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 [8].

Besides, we also considered section 1.7 of ACM code, which ensured us to maintain user confidentiality [8]. As personal privacy is one of the most important concerns for patients, we promise that we would not collect users' health information for trade, business, and all other unethical purposes. In this project, we were trying to reduce the number of wires used and made 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 [8].

5.4 Future work

While we were able to meet most of the requirements and goals, the ultimate goal is to expand our project into creating a 12-lead ECG. Nevertheless, we would like to propose a more realistic goal for future semester students with our sponsor, which is to create a 6-lead wireless ECG device. This can be done by simply attaching one more electrode on the body.



LEAD	Positive Electrode
aVR	RA
aVL	LA
aVF	LL

Figure 22. Visual representation of the three augmented limb leads in a triangle. Adapted from [5]

Our device already contains electrode placements for RA, LA, LL, and placing an extra electrode at the center of these three nodes would allow measurements of three more leads, commonly referred to as the augmented limb leads. This configuration with our design would only require one extra ECG electrode placement. Though it seems to require three more signal processing chips, only one more is needed and the other two can be calculated digitally, on the software. For instance, we can consider a scenario using 5 electrode placements and 3 signal processing chips, with electrode measurements taken from RA, LA, LL, RL, and the center of body (center):

$$Lead\ I \ = LA \ - \ RA \quad * \ Chip\#1$$

$$Lead\ III \ = LL \ - \ LA \quad * \ Chip\#2$$

$$Lead\ aVR\ =\ RA\ -\ Center\quad *\ Chip\#3$$

$$Lead\ II = LL\ -\ RA = Lead\ I\ +\ Lead\ III\quad *\ Calculation\ \#1$$

$$Lead\ aVL\ = LA -\ Center\ = Lead\ I\ +\ Lead\ aVR\quad *\ Calculation\ \#2$$

$$Lead\ aVF\ = LL -\ Center\ = Lead\ II\ +\ Lead\ aVR\quad *\ Calculation\ \#3$$

Nevertheless, the remaining challenge is to constrain the size of the device and maintain a suitable battery life. Appropriate microprocessor should be chosen to consider the number of inputs.

Though the AD8232 chip provided amplification and filtering functionalities, the configuration of the AD8232 can be improved to accomplish higher resolution to the ADC, as we were able to achieve maximum amplitude of 2.25V while the maximum input voltage allowed for ADC is 3.3V. Further filtering techniques in the digital domain could be implemented to further remove unwanted noise components. Upon invention of the ultimate 12-lead wireless ECG, the product will have to meet the standards for FDA approvals.

References

[1] "Cardiovascular diseases," *World Health Organization*. [Online]. Available: https://www.who.int/health-topics/cardiovascular-diseases#tab=tab_1. [Accessed: 03-May-2022].

[2] S. K. Roy, S. U. Shah, E. Villa-Lopez, M. Murillo, N. Arenas, K. Oshima, R.-K. Chang, M. Lauzon, X. Guo, and P. Pillutla, "Comparison of electrocardiogram quality and clinical interpretations using prepositioned ECG electrodes and conventional individual electrodes," *Journal of Electrocardiology*, 06-Feb-2020. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0022073619309689. [Accessed: 04-May-2022].

[3] "Cardiovascular diseases," *World Health Organization*. [Online]. Available: https://www.who.int/health-topics/cardiovascular-diseases#tab=tab_1. [Accessed: 03-May-2022].

[4] Analog devices, "Single-Lead, Heart Rate Monitor Front End," AD8232 datasheet, Aug. 2012 [Revised Mar. 202020].

[5] ThePhysiologist, "The ECG leads, polarity and Einthoven's triangle," *The Student Physiologist*, 15-Nov-2016. [Online]. Available: https://thephysiologist.org/study-materials/the-ecg-leads-polarity-and-einthovens-triangle/. [Accessed: 03-May-2022].

[6] "Encoding Audio and Video", Bitesize. [Online]. Available: https://www.bbc.co.uk/bitesize/guides/z7vc7ty/revision/4

[7] Microcontrollerslab.com. 2022. [Online] Available: https://microcontrollerslab.com/esp32-bluetooth-low-energy-ble-using-arduino-ide/ [Accessed: 5 May 2022].

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

Appendix A Requirement and Verification Table

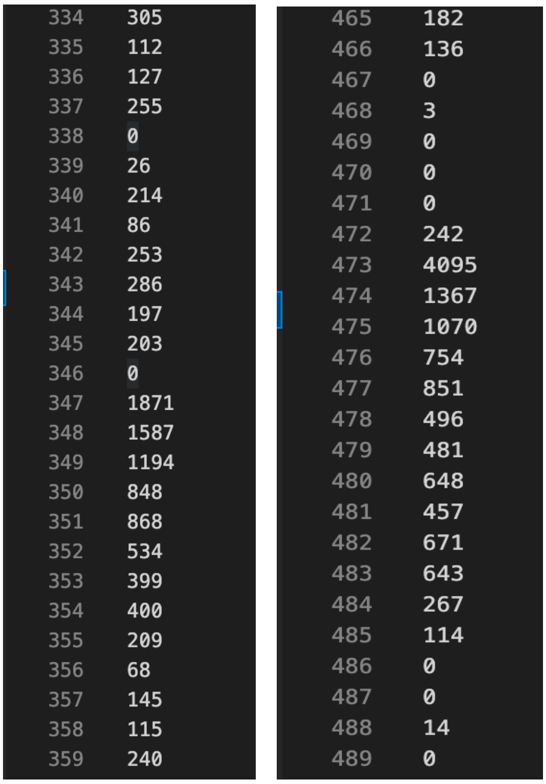
Table 4. Requirements and Verifications

Skin Patch Subsystem		
Requirement	Verification	Verification status
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.	Yes
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	Yes
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.	Yes
Power Subsystem		
Requirement	Verification	Verification status
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.	Yes
Signal Amplification and Filtering Subsystem		
Requirement	Verification	Verification status
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	Yes

	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.	Yes
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.	No
Data Transmission Subsystem		
Requirement	Verification	Verification status
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, 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 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)	Yes
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	Yes. The required transmission rate depends on the implementation. The implementation has changed, so the minimum transfer rate has changed to 8 Kbps, which the system achieved.

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) 5m apart 2. Send a set of sample data points from the hub to the computer 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	Yes
Data Visualization Subsystem		
Requirement	Verification	Verification status
This module should successfully display 3 graphs (Lead 1, Lead 2, and Lead 3).	1. Verify if 3 graphs are displayed on a computer by counting how many graphs are visually present on the computer screen	Yes

APPENDIX B Figures



334	305
335	112
336	127
337	255
338	0
339	26
340	214
341	86
342	253
343	286
344	197
345	203
346	0
347	1871
348	1587
349	1194
350	848
351	868
352	534
353	399
354	400
355	209
356	68
357	145
358	115
359	240

465	182
466	136
467	0
468	3
469	0
470	0
471	0
472	242
473	4095
474	1367
475	1070
476	754
477	851
478	496
479	481
480	648
481	457
482	671
483	643
484	267
485	114
486	0
487	0
488	14
489	0

Figure 24. B-1. Data of Lead 1 and Lead 3 are received and categorized into the correct Lead data files.

```
2352    4095
2353    949
2354    574
2355    369
2356    266
2357    173
2358    73
2359    241
2360    0
2361    212
2362    26
2363    37
2364    324
2365    0
2366    446
2367    0
2368    434
2369    145
2370    32
2371    305
2372    0
2373    249
2374    0
2375    0
2376    66
2377    160
2378    10
2379    231
2380    0
2381    86
2382    0
2383    201
```

Figure 25. B-2. Data Received in the Data Visualization Subsystem

APPENDIX C Circuit Configuration from the AD8232 Datasheet

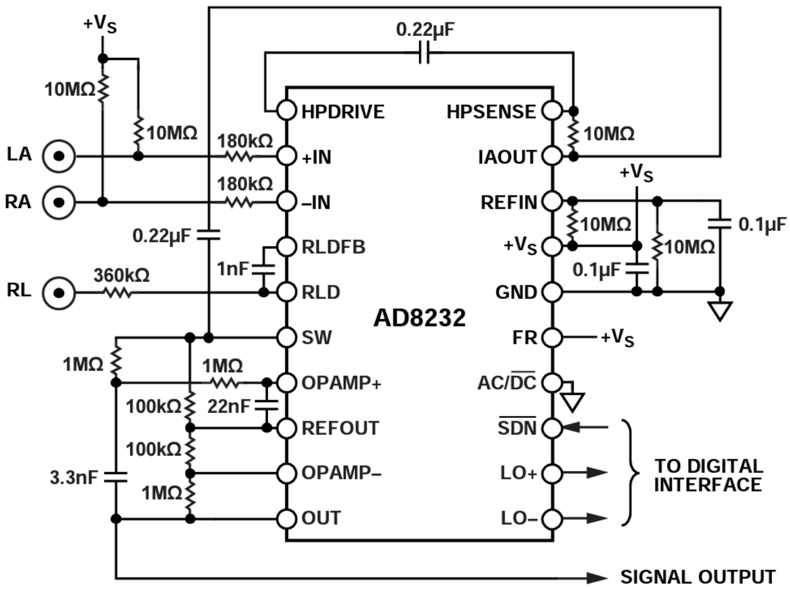


Figure 26. Circuit configuration from the AD8232 Datasheet