ECG Signal Acquisition and Analysis Using Arduino and MATLAB

By: Jonathan Guaman

Start date: 11/17/2024
End date: 01/16/2025

Introduction:

Electrocardiography(ECG or EKG) is a simple procedure to evaluate one’s heart. ECG reports are crucial to understand a patient's cardiac conditions. The idea of ECG might seem troublesome to patients, but in reality, it is a simple concept.

What is ECG?

As stated before, ECG is a simple and non-harming method that measures the heart's electrical activity, including rate and rhythm. To understand more about ECG one needs to know the difference between ECG electrodes and ECG leads:

- **Electrode:** Pad that are attached and allows the recording of electrical current.
- **Leads:** are the graphical description of the heart's electrical activity and are made by analyzing the readings of the electrodes.

The typical version of ECG is a *12-lead* ECG(Fig 1), the 12 leads is made up of two types of ECG lead limn leads and chest lead.

Figure 1: 12-lead ECG. Black wires are the ECG lead. The pads are the electrodes.

Electrophysiology of ECG Leads

Electric current is generated by the movement of charged particles. In the human body, these particles are represented by intracellular and extracellular ions. These ions travel across cell membranes and between cells via gap junctions. When ions move across the cell membrane, the cell can depolarize and repolarize. Traveling between cells via gap junctions allows depolarization to spread across multiple cells.

Electrical potential difference is defined as the electrical difference between two measurement points. In the human body, the electrical potential difference originates from the electrical impulses that travel through the heart. In an ECG, these two measurement points are the skin electrodes. Therefore, the electrical potential difference is the difference in electrical potential between two or more electrodes. This difference is detected because the entire human body acts as an electrical conductor. Hence, placing electrodes on the human body allows for the detection of electrical currents.

ECG WaveForms:

The result of an ECG test is a graph consisting of waveforms. These waveforms represent the electrical events in the heart cycle.

P-Wave:

The P-wave is the first deflection from the baseline voltage observed on an ECG and represents the electrical depolarization of the atria of the heart. This depolarization is the passage of current sequentially through the heart muscle, leading to the contraction of the atria. The duration of the P-wave is less than 120 ms.

P-waves originate from the sinoatrial node, a small cluster of muscle fibers located in the right atrium of the heart. The electrical signal disperses into both the right and left atria. Depolarization of the right atrium contributes to the early part of the P-wave, while depolarization of the left atrium forms the middle and terminal portions of the P-wave.

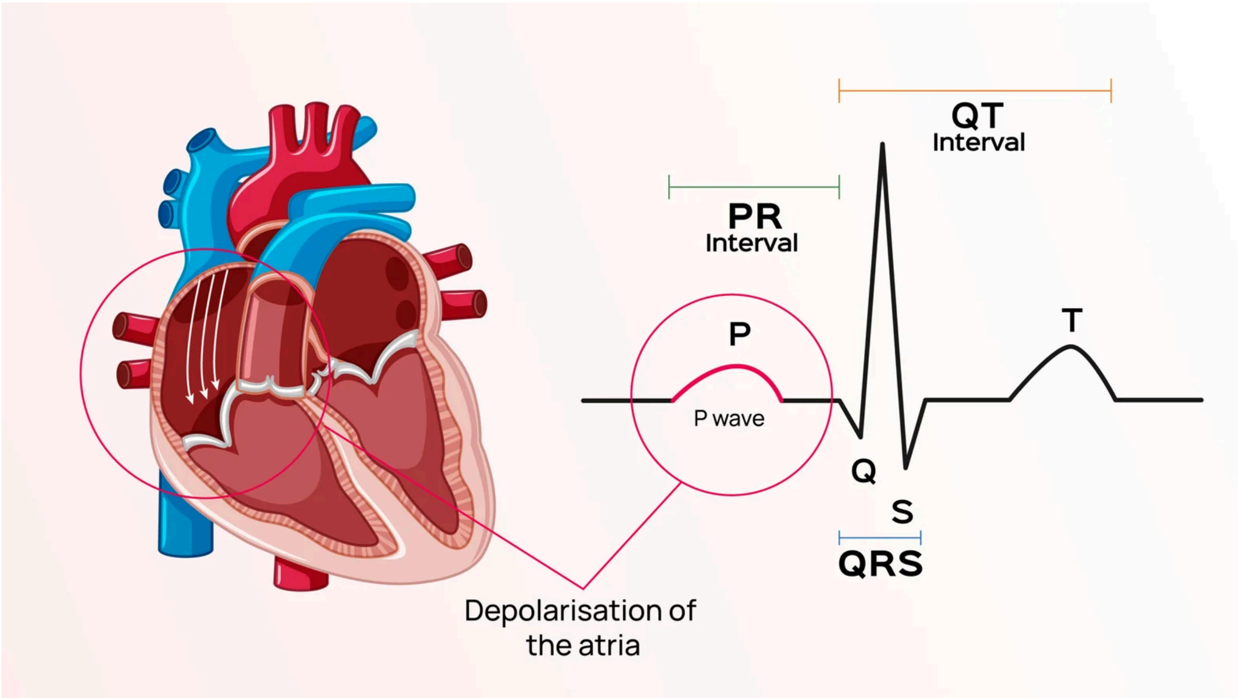

Figure 2: P-wave of ECG(*Dr. Drivya Shrinivas/SunFox,2024*)

PR Interval:

The PR interval refers to the time period between the P-wave and the R-wave. It is a part of the ECG that represents the time it takes for the electrical impulse to travel from the sinoatrial node in the atria to the ventricles. The PR interval starts at the beginning of the P-wave and ends at the beginning of the QRS complex, lasting between 120-200 milliseconds.

To measure the PR interval, one must identify the P-wave (Figure 1) and locate the QRS complex, which follows a rapid downward and upward deflection. The PR interval is the time between the start of the P-wave and the start of the QRS complex. This interval is typically measured in milliseconds using the ECG paper's grid, where each small square usually represents 40 ms. An accurate measurement of the PR interval is crucial for diagnosing heart conditions.

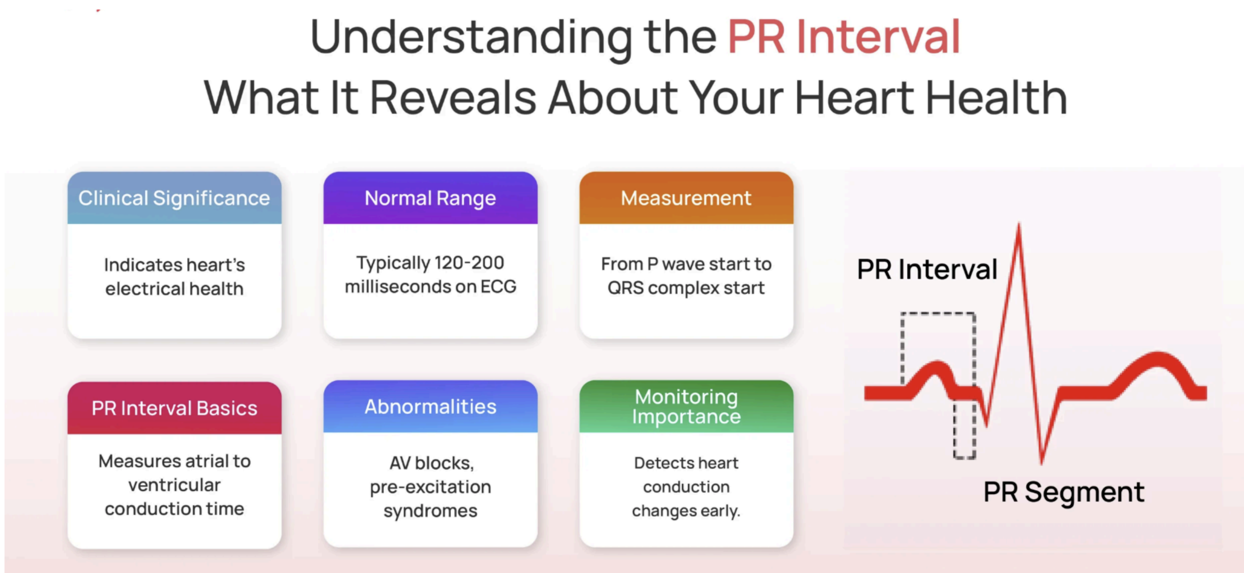

Figure 3- PR interval(*Mr. Ritesh Sharma/SunFox 2024*)

QRS Complex:

The QRS complex can be found by locating the spike in ECG reports. It represents the depolarization of the ventricles and marks the beginning of their contraction.

The QRS complex is made up of the Q, R, and S waves. In ECG reports, the Q wave is negative, followed by a positive deflection known as the R wave, and then a negative deflection called the S wave. The duration of the QRS complex typically ranges from 0.08 to 0.1 seconds. A normal duration lasts between 0.1 and 0.12 seconds, while anything longer indicates an abnormal reading.

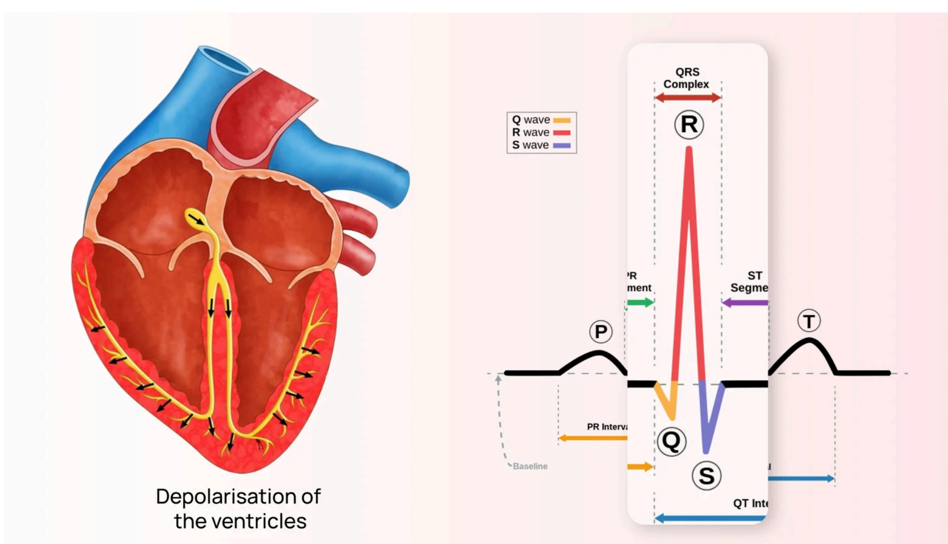

Figure 4 - QRS complex (*Partha Sharma/SunFox 2024*)

T-Wave:

The T-wave follows the QRS complex and represents the repolarization of the ventricles. Repolarization is the process of restoring the electrical charge balance in the cardiac cells, preparing them for the next depolarization. The T-wave is typically a positive deflection, though it can sometimes be negative depending on the leads and heart conditions. The duration of the T-wave varies but is usually between .16 and .25 milliseconds.

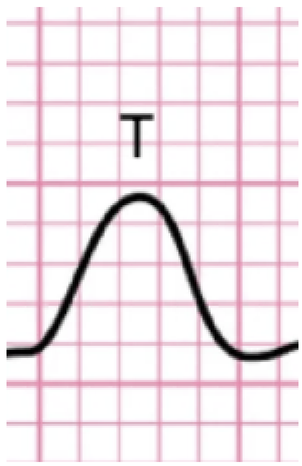

Figure 5- T-Wave ECG(*Mr. Ritesh Sharma/SunFox 2024*)

System design: Hardware & Software

Objective:

The goal of this project is to use a microcontroller to obtain ECG signals through the AD8232 module and understand these signals through MATLAB.

Hardware Setup

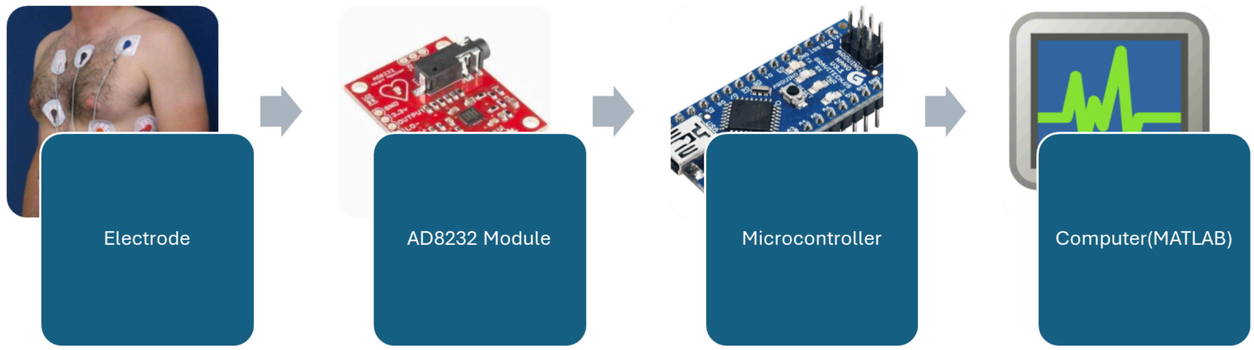

Figure 6- Block Diagram of Hardware Setup

AD8232 Module: Key In Acquiring ECG Signals

The AD8232 is a cost-effective and flexible module design for ECG measurements. It simplifies the process of measuring the electrical activity of the heart through signal processing. In this project, the module is used as a bridge between the human body and the microcontroller.

Features:

- **Signal and Conditiong:** Reduce noise and isolate ECG signal from unwanted electrical interference.
- **Low Power Consumption:** Designed for portable applications
- **Built-in Leads-Off Detection:** Ensure reliability of signal by reassuring that electrodes are connected

Role:

Electrode Connection
- Electrodes are attached to capture hearts electrical activity

Signal Conditioning
- AD8232 amplifies and filter raw signals, removing noise for future process

Microcontroller Interface
- Conditioned signal is sent to microcontroller for digitalization and data transfer

MATLAB Analysis
- Receive ECG data and transform it to visualize waveforms

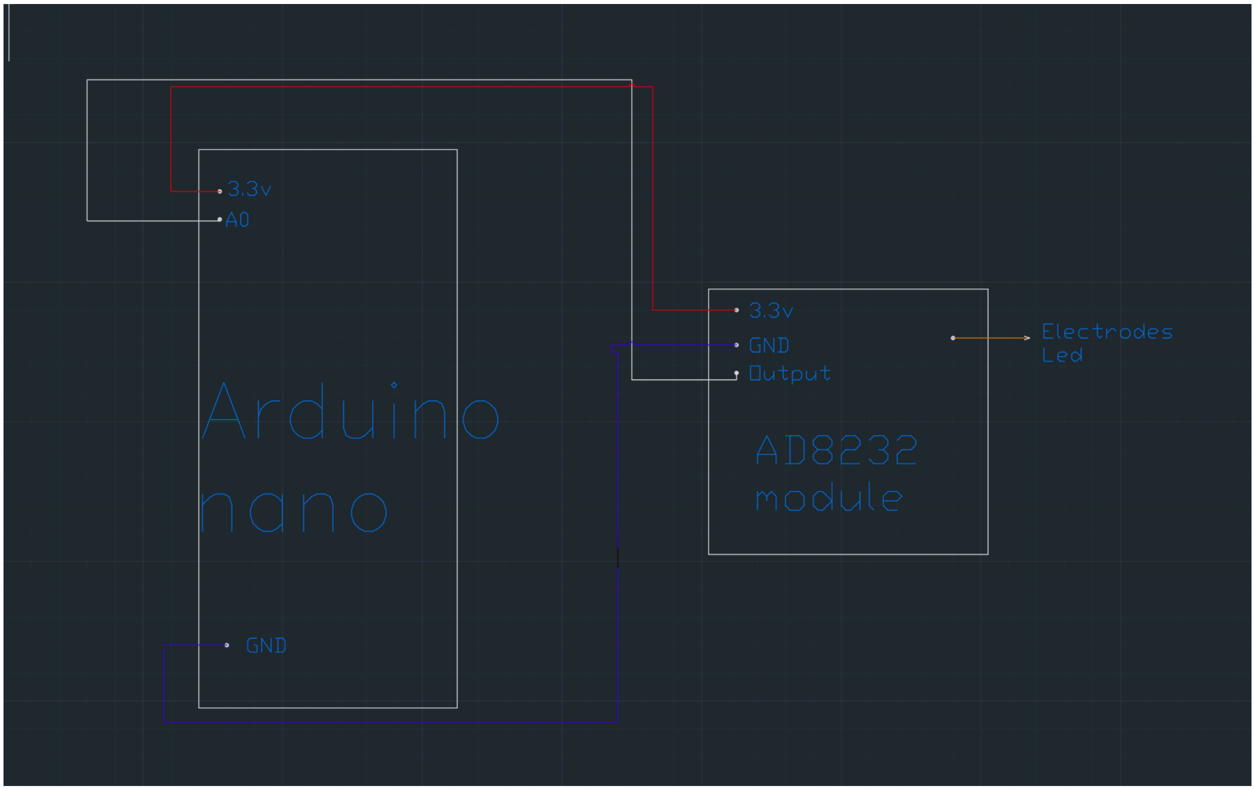

Figure 7 - Circuit Schematic

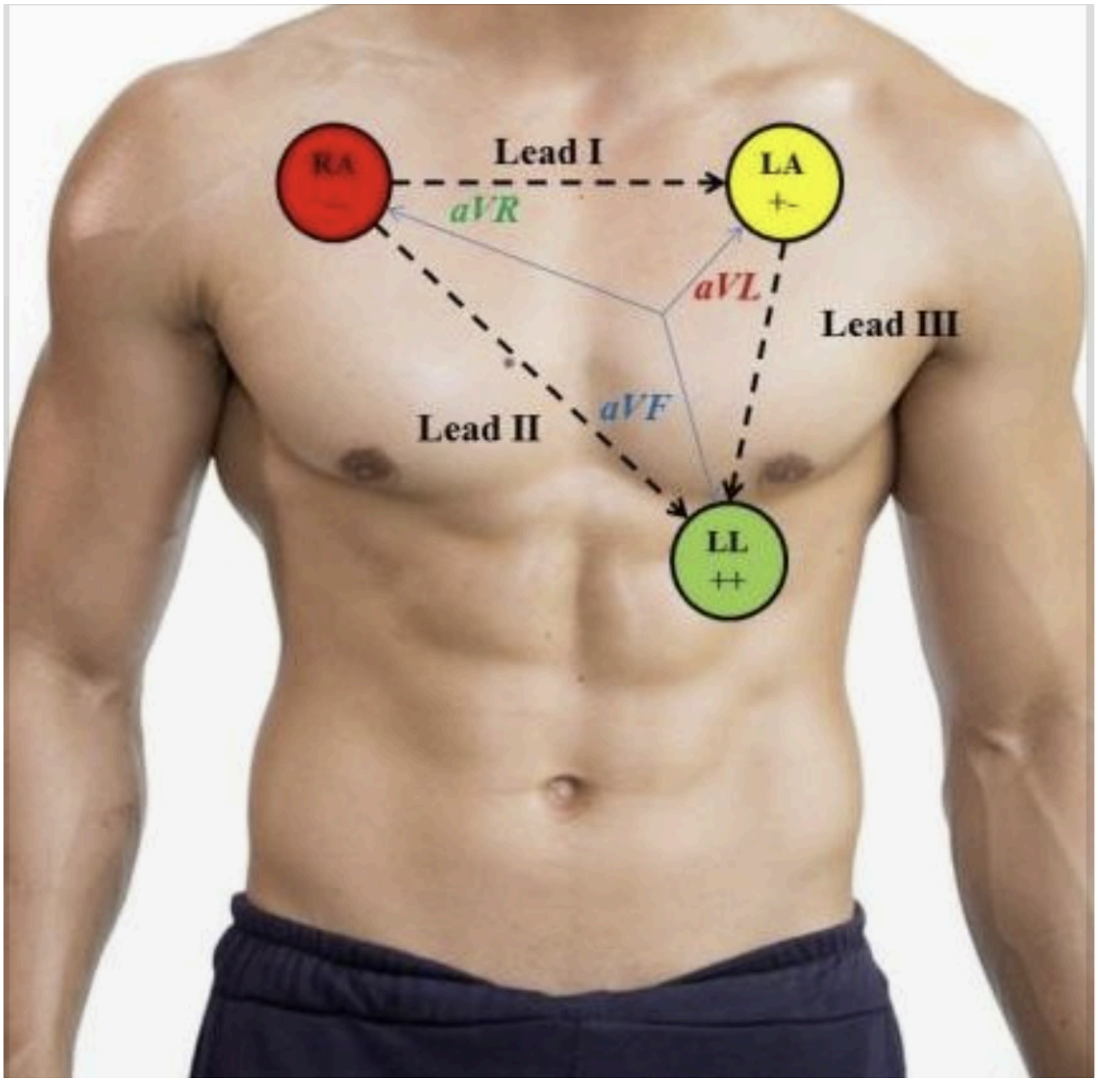

Figure 8 - Electrode placements

Software Integration

Arduino used MATLAB to process the ECG signal. It will become a clear and comprehensible waveform and allow key components of ECG waves such as P-wave, QRS complex, and T-wave to be analyzed.

Results

Data Visualisation:

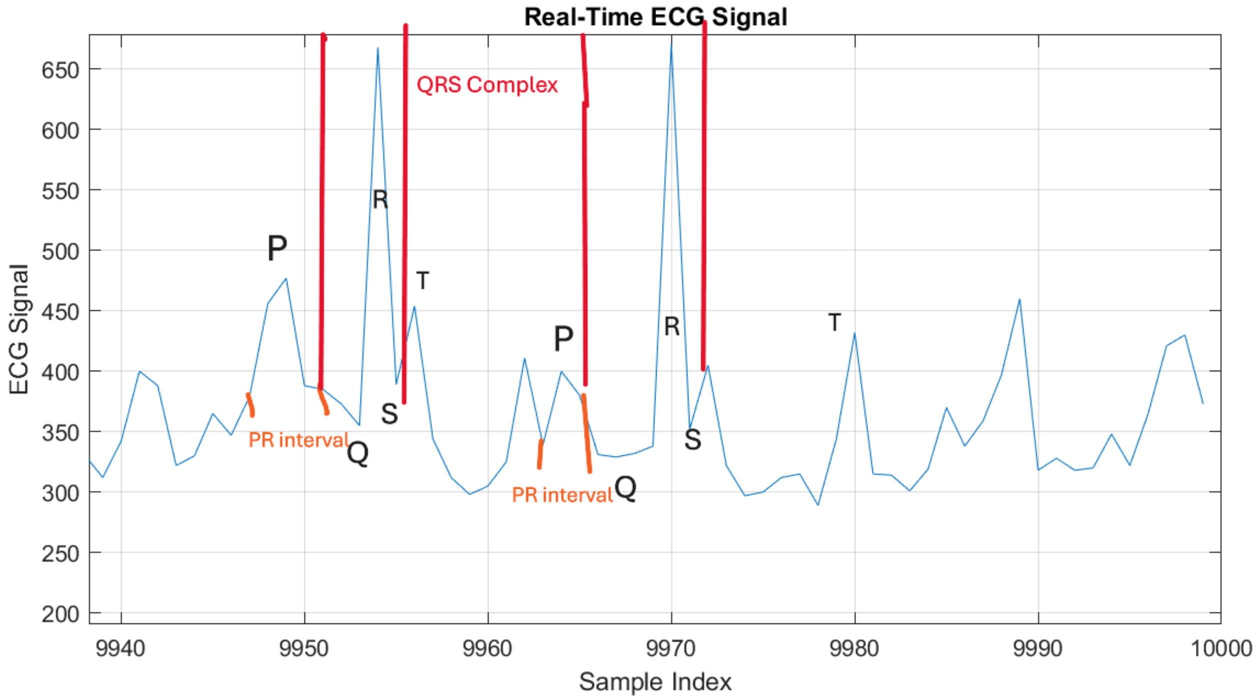

Figure 8- MATLAB ECG Waveform

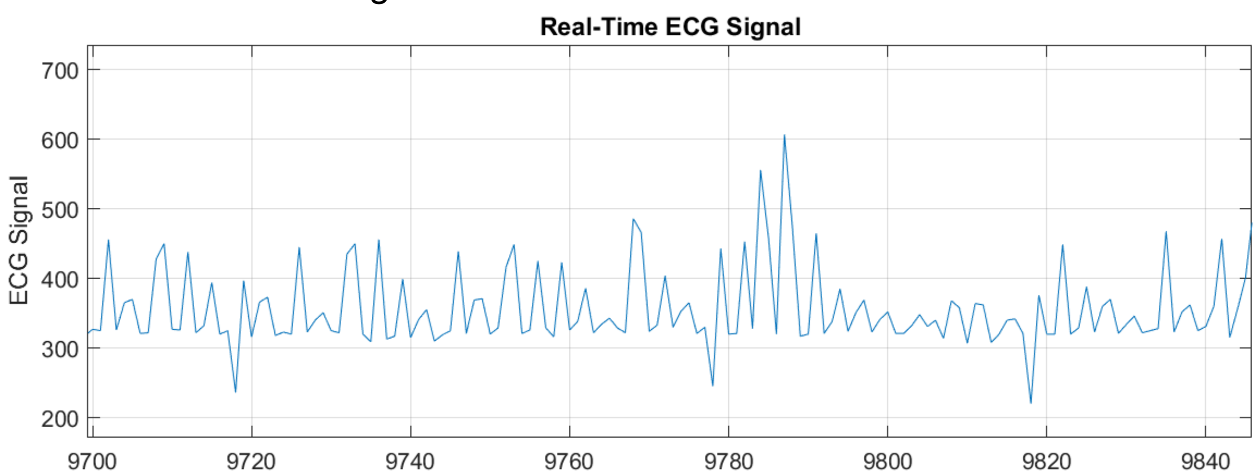

Figure 9 - WaveForm Disruptsnce

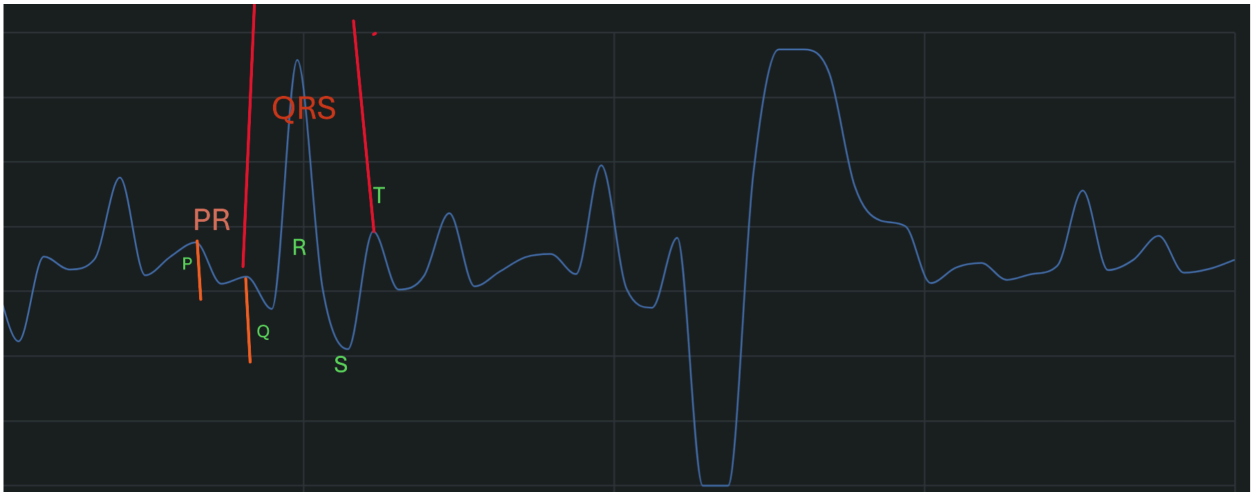

Figure 10- ECG Waveform Arduino version
Figure 11 - Hospital

Analysis:

The ECG waveform (Figure 8), captured and processed using MATLAB, demonstrates the key features of a typical ECG signal. The annotations highlight the real-time ECG components and their characteristics.

- P-Wave: Represents atrial depolarization and is observed as the initial small upward deflection in the waveform.
- PR Interval: Highlighted in orange on the graph, this interval indicates the delay in electrical conduction between the atria and ventricles.
- QRS Complex: The most prominent feature of the waveform, marked in red, reflects ventricular depolarization and subsequent contraction.
- T-Wave: Following the QRS complex, the T-wave, seen as the next upward deflection, signifies ventricular repolarization.

The MATLAB-generated waveform clearly demonstrates the module's capability to capture these critical cardiac events. However, inconsistencies in the amplitude suggest noise interference, likely caused by issues such as electrode placement or environmental factors.

When comparing the MATLAB-generated ECG waveform to hospital-grade ECGs, significant differences become apparent in their ability to distinguish between actual ECG signals and noise. Medical-grade equipment is designed to effectively filter out noise, presenting it as a straight line, whereas the data collected in this project does not. For example, the amplitude readings in Figure 8 include noise artifacts that were captured and processed alongside the ECG signal. Hospital-grade machines, by contrast, are able to disregard these artifacts, providing cleaner and more accurate readings.

This inability to differentiate noise from the ECG signal could lead to misinterpretation of the data. For instance, Figure 10 illustrates a significant drop in the QRS complex, which, if accurate, would suggest a cardiac issue requiring immediate medical attention. However, this is incorrect, as I have no history of heart-related conditions. The irregularity is instead attributed to noise interference and not an accurate representation of heart activity.

Figure 9 further highlights the impact of noise during signal acquisition. These readings do not resemble those in Figure 8 and are challenging to interpret. While some ECG signals may be present, they are obscured by amplitude variations that exceed or fall below actual ECG values, reinforcing the idea of noise interference.

The signal quality of the AD8232 module is generally clear; however, inaccuracies were frequently observed. As shown in Figure 9, the module is capable of capturing ECG signals, but it is highly susceptible to disruptions. While some waveforms closely resemble accurate ECG patterns, others deviate significantly or provide misleading information about heart function. These distortions are primarily caused by noise interference, which the module cannot entirely filter due to its limitations compared to hospital-grade devices.

Noise interference, as seen in the graphs, often stems from factors such as electrode lead connections or patient movement. Even slight movements of the electrode cables can result in significant variations in the amplitude of the ECG signal. Despite this, the Arduino-MATLAB integration proved effective in detecting and visualizing these noise artifacts as part of the ECG signal. Although some of the captured signals were inaccurate, the system's ability to identify and present these artifacts highlights its potential for signal processing.

Improving the accuracy of ECG signal readings will likely involve refining the software code and collecting additional data in various environmental conditions. This would help differentiate true ECG signals from noise artifacts, ultimately enhancing the system's reliability and bringing it closer to the performance of advanced ECG monitoring devices.

Discussion:

During the research, unexpected results were frequently observed. These issues are believed to have stemmed from noise interference, improper electrode placement, and potential damage to the AD8232 module. While noise interference and electrode placement were identified as contributing factors, the primary issue appeared to be the AD8232 module itself. The module’s affordability and ease of use make it an excellent tool for capturing ECG signals; however, its heat resistance poses a challenge. During the soldering process, when attaching ports to the module, it became excessively hot. This heat may have damaged the module, potentially leading to inaccurate waveform readings.

Several challenges arose throughout the project. A key issue involved the electrodes connected to the AD8232 module. During the early testing phase, the amplitude of the ECG signal consistently ranged between 711 and 715, producing a flat line rather than the expected waveform. Further investigation revealed that the problem lay with the electrodes. Even when the electrodes were disconnected from the module, the signal remained within the same range. Replacing the electrodes and properly attaching them to the body resolved the issue, allowing the system to generate accurate ECG waveforms instead of a constant line.

Another significant challenge was establishing reliable communication between the microcontroller and MATLAB via the serial ports. During data transmission, the microcontroller had to be connected to the computer through a USB port. Initially, checking amplitude values using the Arduino IDE’s Serial Monitor resulted in a loss of communication with MATLAB. The solution was to close the Serial Monitor in the Arduino IDE and instead monitor the amplitude values directly in MATLAB. Although this issue was resolved, it sparked curiosity about potential improvements for future projects. For instance, using a microcontroller with server connectivity could streamline data transmission and enhance ECG waveform generation—a concept to explore in subsequent work.

Conclusion:

This research project demonstrates the potential for creating a low-cost and effective system for capturing ECG signals using Arduino and MATLAB. While the results may not match the precision and reliability of hospital-grade equipment, the system successfully captures key cardiac features, offering an accessible solution for individuals seeking an affordable way to monitor their cardiac health.

I acknowledge the possibility of errors during this research; however, mistakes are a crucial part of the learning process, enabling growth and improvement. If given the opportunity, I would gladly refine and enhance this project further. Beyond the development of an ECG signaling system, this project has been instrumental in sharpening my technical skills and preparing me for future career opportunities.

As this project comes to a close, I would like to express my gratitude to my professor, Dr. Artan, for inspiring this idea and providing invaluable guidance throughout the research process.

Work cited:

- Divya, Shrinivas. "P Wave ECG Abnormalities and Its Role in Cardiac Wellness." *Https://Sunfox.In*, 10 July 2024, sunfox.in/blogs/p-wave-ecg-abnormalities-and-their-role-in-cardiac-wellness/.
-
- Sharma, Ritesh. "Understanding a Normal ECG Report: A Comprehensive Guide." *Https://Sunfox.In*, 1 July 2024, sunfox.in/blogs/understanding-a-normal-ecg-report/
- "Electrocardiogram." *Johns Hopkins Medicine*, 13 Mar. 2024, www.hopkinsmedicine.org/health/treatment-tests-and-therapies/electrocardiogram#:~:text=An%20electrocardiogram%20(ECG%20or%20EKG,ECG%20machine%20by%20lead%20wires
- Sharma, Ritesh. "ECG Full Form: Understanding Electrocardiogram." *Https://Sunfox.In*, 20 Sept. 2024, sunfox.in/blogs/ecg-full-form/
- Sharma, Ritesh. "PR Interval." *Https://Sunfox.In*, 29 June 2024, sunfox.in/blogs/understanding-the-pr-interval/.
- Sharma, Parth. "Understanding QRS Complex Abnormalities in Cardiac Health." *Https://Sunfox.In*, 10 July 2024, sunfox.in/blogs/qrs-complex-abnormalities-in-cardiac-health/.
- Sharma, Ritesh. "Understanding St Elevation ECG: A Vital Tool in Cardiac Care." *Https://Sunfox.In*, 12 Aug. 2024, sunfox.in/blogs/understanding-st-elevation-ecg/.
-
- "The ECG Leads: Electrodes, Limb Leads, Chest (Precordial) Leads and the 12-Lead ECG." *Cardiovascular Education*, 25 June 2023, ecgwaves.com/topic/ekg-ecg-leads-electrodes-systems-limb-chest-precordial/#:~:text=An%20electrode%20is%20a%20conductive,created%20by%20analyzing%20several%20electrodes
-