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Design of Internet of Things (IoT) Based Wearable Electrocardiogram

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Abstract - An electrocardiogram is a recording of the electrical activity of the heart. It is a crucial technology for the early detection and diagnosis of heart-related issues such as heart arrhythmia and other abnormalities in the heart. Most ECG machines, both the handheld single lead devices and standard 12 lead ECGs found in hospitals make use of adhesive gel electrodes which are uncomfortable for long periods among other issues. These devices are also quite expensive for the average Ghanaian. The standard ECGs found in hospitals also lack remote capability and the ability to transfer and store results instantly over the internet. This project explores the design of a wearable, low-cost, IoT device that will cater to each of these limitations. Textile electrodes sewn into a shirt are used in place of the gel electrodes to avoid irritability and the wearing off of electrodes in long-term usage. A design based on a low-cost microcontroller, the esp8266 together with other circuit components is employed to ensure the system is affordable and has remote capability. Digital processing techniques are also implemented both in real-time and through post-processing in MATLAB to provide alternative means of processing the signal from the electrodes. Results obtained from testing show that the prototype could provide accurate ECG results remotely both in real time and for storage and was comfortable and affordable for the user.

Keywords - *MATLAB, Electrocardiogram, Electrodes, Printed Circuit Board.*

1. Introduction

1.1 Background

It is often common knowledge and studies also prove that cardiovascular diseases are one of the main causes of death around the world. "In 2015, 2,712 630 resident deaths were registered in the United States, and 10 leading causes accounted for 74.2% of all registered deaths. Of the 10 leading causes of death, heart disease was No. 1" [1]. One of the primary means of early diagnosis of heart disease and irregularities in the functioning of the heart is using electrocardiograms. An electrocardiogram provides information about the heart rate and rhythm by recording the electrical activities of the heart. It is an effective tool and procedure for detecting abnormal heart rhythms and checking on the general conditions of the heart.

1.2 Problem Definition

In this project, one of the key issues being tackled was cost. "Compact personal-use ECG devices' costs start at about $50 and go up to $300 or more depending on the brand and model. Clinical and hospital-grade ECG monitors typically begin at around $200 and can go up to several thousand dollars each" [2] and this is quite expensive for the average Ghanaian. Therefore, for patients in need of constant monitoring, the price of the ECG becomes a major hurdle for them. Also, the standard 12-lead ECGs cause some discomfort to patients in prolonged usage due to the irritation caused by the adhesive gel electrodes. Comfort is not the only issue with these gel electrodes as it may affect the signal quality during long-term monitoring [3]. As the gel dries up it loses some amount of contact with the skin and begins to produce inaccurate readings. Most standard ECG machines are also not cloud-enabled and do not offer easy access, storage, and retrieval of ECG information remotely. However, it is vital to be able to keep a record of a patient's reading since this can be useful in diagnosis.

1.3 Objectives of the Project Work

- Design of an alternative ECG device/product that would be more affordable: One of the major goals would be to significantly reduce the production cost and selling price of this device to make it more accessible to the Ghanaian community. Although it will be less costly, there should be no trade-offs in terms of accuracy and quality of readings as this would defeat the entire purpose of the test. The goal is for the average Ghanaian to be able to accurately monitor their heart without significant financial loss.
- Provide more comfort: As discussed earlier the current 12 lead ECG machines make use of adhesive gel electrodes which cause discomfort to patients among other issues. A better, more

suitable, and more comfortable material could replace these gel electrodes which would provide equally accurate readings. Alternatively, necessary modifications or improvements could be made to these gel electrodes which would solve all pertinent issues.

- Long-term monitoring without any hitches – To avoid the risk of making readings at times where the issue may not be visible, this project should be able to offer prolonged monitoring over an extended period. With this in place, diagnoses can be made with more certainty, and patients already requiring long-term monitoring can also make use of this product.
- IoT Enabled: The product should be able to communicate with cloud services such that the ECG information may be stored and viewed on any device at any time. The stored data can then be analyzed to make the necessary derivations and conclusions.

2. Materials and Methods

2.1. Introduction and Technical Approach

The goal of this project is to design and implement an IoT-based wearable and affordable ECG device to provide both short-term and long-term monitoring for people who have limited access. This product will make use of textile electrodes instead of gel electrodes to provide more comfort. It will also be very affordable and accessible to the average Ghanaian. It will provide accurate and reliable readings and will keep a record of all readings for long-term patients for future referral. To create an ECG, firstly the signal needs to be obtained from the body using electrodes. There are different systems for electrode placement, therefore for this project Einthoven's triangle, consisting of 3 electrodes, is the chosen system. This theory depicts an imaginary equilateral triangle having the heart at its center which is formed by lines that represent the three standard limb leads of the electrocardiogram. These leads are the right arm (RA), left arm (LA), and left leg (LL). Einthoven's Law explains that Lead II's complex is equal to the sum of the corresponding complexes in Leads I and III and is given as II = I + III making them electrically equilateral [4]. Based on this theory a three-lead ECG can be generated which according to a study done by the Scandinavian Journal of primary health care has an accuracy level of 96.6% [5]. After the signal from the electrodes has been obtained it needs to undergo signal conditioning which includes amplification and filtration of the signal before conversion into digital form. There are two ways of achieving this, either through analog signal processing or digital signal processing and for the purposes of this project, each of these methods is going to be used and implemented.

2.2 General System Requirements:

Cost: The system needs to be affordable for the average Ghanaian such that more Ghanaians will have access to vital diagnostic information about heart diseases to prevent critical illness and untimately death.

Lightweight and comfortable: The system needs to be lightweight since it is going to be worn for extended periods. Itchiness and electrodes coming off must also be guarded against by using textile electrodes instead of gel electrodes. This is essential as discomfort due to heaviness or itchiness may disrupt the ECG readings and result in an inaccurate diagnosis.

Long-term monitoring: The product must be suitable for long-term monitoring by providing reliable and accurate readings and having a system in place to keep a record of these readings and to make them easily accessible. Abnormality detection: The system should be able to detect abnormalities in the rhythm of the heart by extracting information about the peaks of the graph.

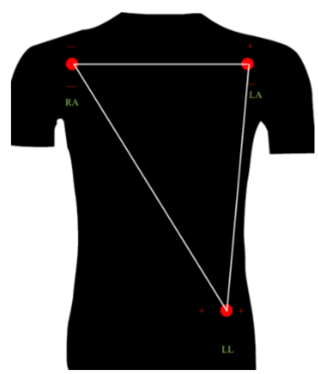

Figure 2.1:Proposed shirt design showing electrode placement

2.3 Analog Signal Processing System Design

2.3.1. Requirements

- High input impedance to prevent distortion of the measured signal.
- High common-mode rejection ratio to suppress common-mode interference.
- The system should be small (<15cm^2) to ensure portability.
- High sensitivity (10mm/mV) for high responsive to weak ECG signals
- High accuracy of measurements and precision as well.

- Low power consumption.

2.3.2. Materials

- Textile electrode
- LM358 OpAmp
- ESP8266 Microcontroller
- Voltage Regulator (LD11117V33)
- Power Source (Lithium-Ion Battery)
- Resistors
- Capacitors

2.3.3 System Block Diagram

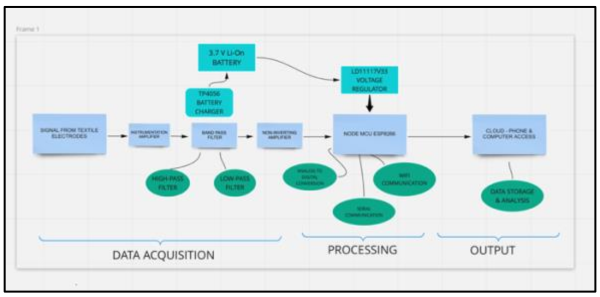

Figure 2.2: System block diagram

2.3.4. Circuit Design

The circuit diagram was designed using NI Multisim software. Figure 2.3 shows the various connections between the components listed in Section 2.3.2

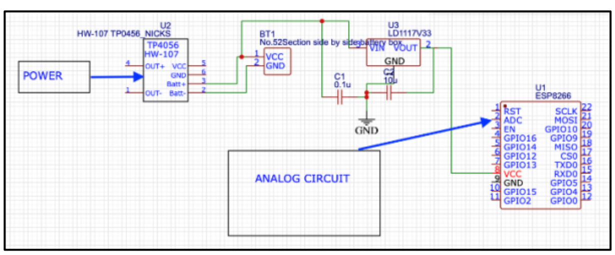

Figure 2.3: Diagram showing connections between components

2.3.5 System Operation

The system operates in stages as depicted by figure 2.2. First, the signal obtained from the electrodes is usually very small at about 1-10 mV and a frequency range of 0.05 - 100 Hz, hence it is amplified by an instrumentation amplifier with a gain of about 200. This brings the voltage to around 1.5V given a typical signal of about 7 mV. An instrumentation amplifier was chosen because it has a high input impedance and a high CMMR which is useful for capturing data from low voltage signals and restricting common-mode interference. The signal is then passed through a low pass filter to help remove higher frequency noise with a cut-off frequency of about 33 Hz. An active 2nd order low pass filter was chosen because they provide better roll-off and a voltage gain as well. The signal then goes through an active high pass filter to eliminate DC offsets that arise because of muscle noise. The cut-off frequency is set to about 0.48 Hz. Subsequently, the filtered signal goes through a non-inverting amplifier with a gain of about 2. It then arrives at the analog input of the ESP8266 for analog to digital conversion. After the digital version of the signal is obtained, the application transport protocol, MQTT together with the chosen communication technology, Wi-Fi is used to publish the data to an online cloud service for storage, further analysis, and easy access on any device.

2.3.6 IoT Architecture

A. Sensor/ECG tracking node: The ECG nodes, which are the electrodes are responsible for obtaining the bio-signals from the patient's body and transporting it through wires to the circuit. The signals are typically very noisy hence most of the noise is eliminated and the signal is amplified before being sent to the processing unit by the analog circuit.

B. Signal processing unit: The microcontroller receives the signals from the previous stage in this unit. To transform the incoming signals to the digital realm, the esp8266 was employed as an intermediate stage. Because the ESP8266 is used as an analog to digital converter, the system is less susceptible to noise than if a specialized ADC system had been used, which would have resulted in more contamination of the bio signals received.

C. Cloud Server & GUI: When the framework receives a large amount of Electrocardiogram data from the tracking node, an IoT cloud provides a speedy and appropriate way to deal with the stored data in the cloud and to display the ECG signal as needed. As a result, an Internet-of-Things cloud is used, based on the method of website assistance, cloud, and data storage. The ECG information can be retrieved by going on to the Internet cloud and using a web browser on any operating system to access a specific web site. As a result, all smart devices, including smartphones, desktops, and laptops, may access the Internet-of-Things cloud [3]. The customers can also get historical data as well as a real-time ECG signal.

2.4 DSP Implementation

2.4.1. Post Processing Using MATLAB

With this approach, after the raw signal is received through the ADC input of the microcontroller it is sent straight to MATLAB through the ThingsSpeak platform for filtering and feature extraction. As explained in section 3.4.1, it is passed through a high pass filter and a moving average filter to obtain the filtered signal. The notch filter may be used if the system was connected to the main power supply rather than a battery source. A script for sending and receiving the signal in MATLAB from the microcontroller is first executed. Afterwards, some features are extracted from the filtered signal mainly using the find peaks function in MATLAB. These include the R peaks, S peaks and Q peaks to form the QRS complex. These features are very useful in giving an accurate diagnosis of heart-related issues such as heart arrhythmia. R peak detection in ECG is one such method that is widely used to diagnose heart rhythm irregularities and estimate heart-rate variability. The heart rate is also calculated using the R peaks.

Based on what was discussed in this chapter, the prototype was developed.

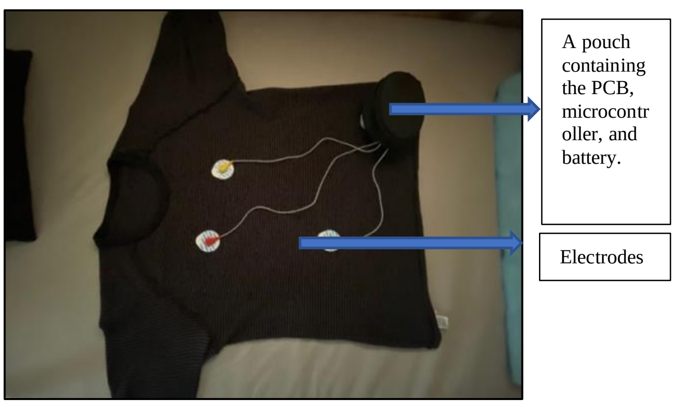

Figure 2.4: Wearable ECG prototype

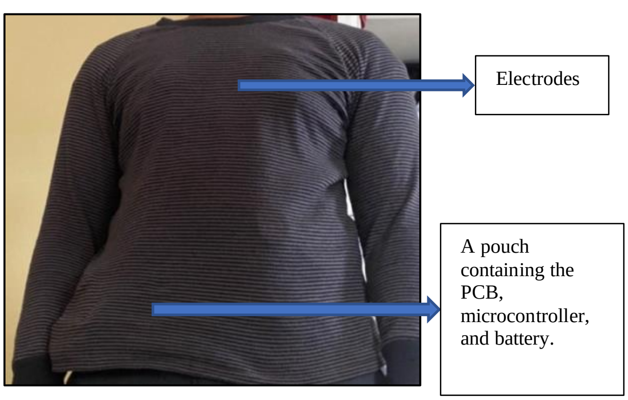

Figure 2.5: Subject wearing prototype 1

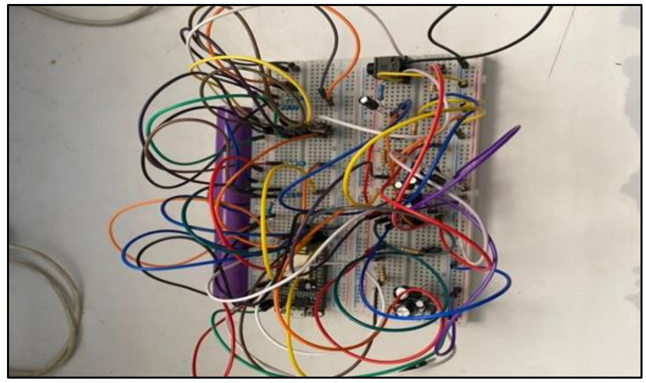

Figure 2.6: Breadboard circuit

After approval was obtained from the Institutional Review Board (IRB), the prototype was tested as seen above. The documents required for IRB approval included a consent form that explained the testing procedure to the prospective subject. The breadboard was used in place of the PCB temporarily as the PCB had not arrived at the time.

3. Results and Discussion

3.1. Software Simulation Results

3.1.1. ASAP System

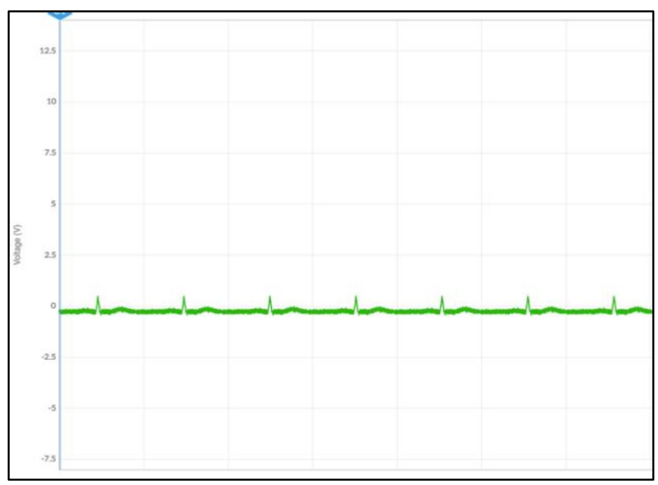

Figure 3.1: Original signal

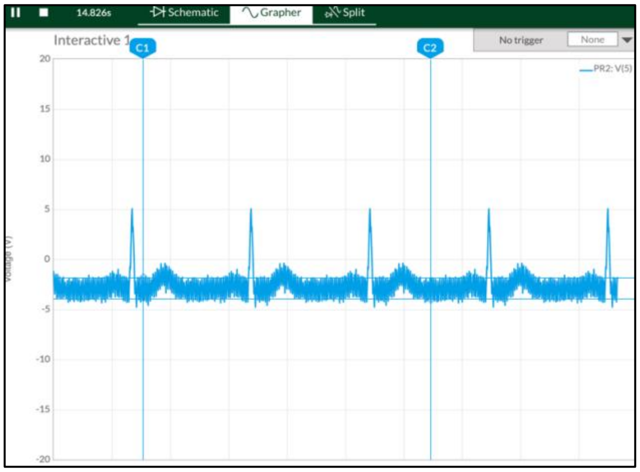

Figure 3.2: Amplified signal

Figure 3.3: Filtered signal

Before the prototype was developed, simulations were ran to ensure the circuitry would work as desired. In Figure 3.1, the original signal which was obtained from an online database is displayed and is shown to contain a lot of noise. This noise is caused by electrodes capturing more than just the electrical activity of the heart. The primary electrical components captured are the myocardium, muscle, skin-electrode interface, and external interference. In figure 3.1 the amplified signal which has been passed through the instrumentation amplifier is displayed. Since this signal was obtained from an online database for simulation purposes, its original voltage was about 800 mV, and this led to an adjustment in the gain of the instrumentation amplifier to 5. As can be seen on the axis of the graph, the signal voltage increased from about 800 mV to 4 V due to this gain. In figure 3.2 the low-frequency noise and high-frequency noise have been removed from the signal leaving the filtered signal.

3.1.2. DSP System

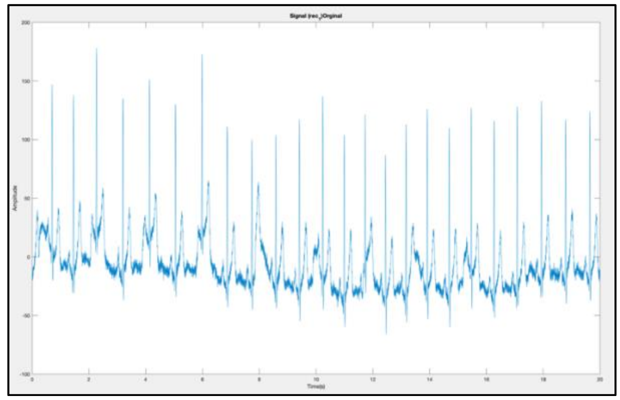

Figure 3.4: Original signal

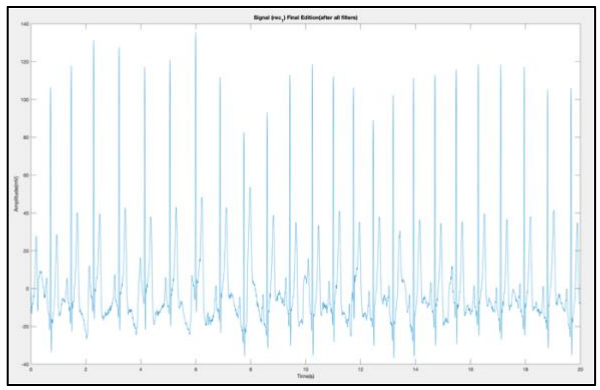

Figure 3.5: Filtered signal

The notch filter was also applied here since there was some power line interference (50 Hz) as the signal was obtained from a device in Russia where the power line frequency is 50 Hz. The signal is noticeably much clearer and more refined compared to the analog processing simulations. A contributing factor to this is the internal tolerances and impedances in the analog components such as the OpAmp which has been incorporated in the simulation software.

3.2. Physical Implementation Results

3.2.1. ASP System

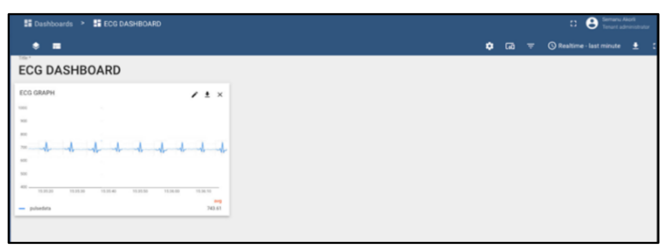

Figure 3.6: Results on ThingsBoard dashboard

Here the ECG information is displayed on the dashboard in real-time. Past recordings are also kept and can be accessed for up to 30 days. The waveform is not exactly as desired here since there is some latency in sending the data to the dashboard. Also, there is little amount of processing power since the resources being used to process the data are from a free cloud-based provider. The QRS complex can be seen with each of the Q, R, and S waves identifiable.

3.2.2. Post-Processing with MATLAB

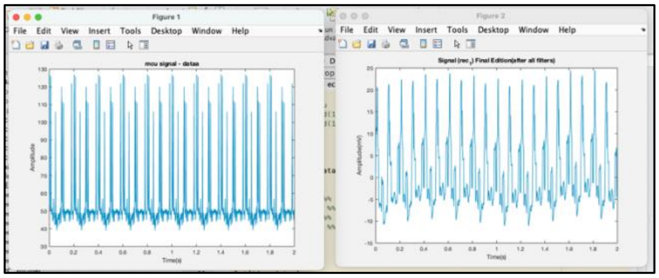

Figure 3.7: MCU Signal before and after filtering in MATLAB

The signal obtained in MATLAB is also much improved since the processing of the signal was done on the local computer rather than a free cloud-based processor which allocates very little processing power.

3.2.3. Data Analysis

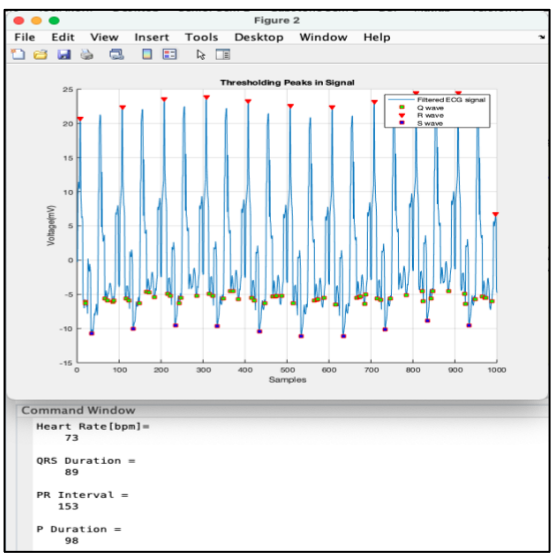

Figure 3.8: Results showing QRS Complex and other features

Here the same functions used in extracting information from the simulated signal are used here on the filtered signal from the prototype with a few adjustments made for the size since the simulated signal is much larger. The size of the signal can be increased by taking the measurements over a longer period as this data was obtained from tests completed within 5 minutes.

3.4. Statistical Analysis & Comparison to Standard ECG

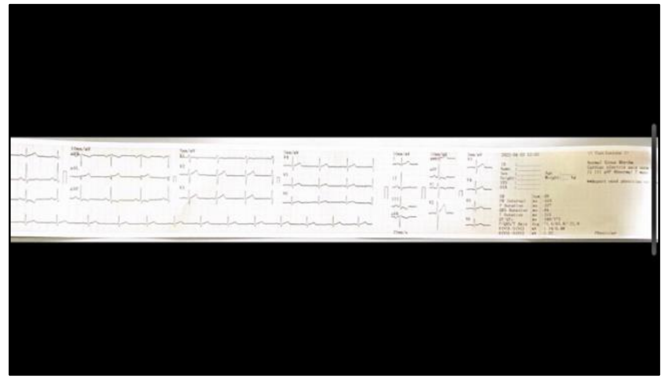

Figure 3.9: ECG Results obtained from a standard 12 lead ECG Device

A 12 lead ECG test was performed on the same subject as was used in testing the prototype at the Ntambea health center and the results above were obtained. The ECG test for the prototype was performed three times to determine the precision of the measurements. To determine the accuracy of the results obtained in the prototype, the PR interval, QRS duration, T duration, and heart rates were compared to those obtained in the standard ECG test to determine if these values were accurate. Values obtained from the standard test as shown in Figure 5.11: are as follows: Heart rate: 69 beats per minute, PR Interval: 163 ms, QRS Duration: 84 ms, P Duration: 107 ms.

3.4.1 Test for Precision

With Standard Deviation (S.D) given as:

$$SD_{sample} = \sqrt{\frac{\sum(x_1 - \overline{x})^2}{n-1}} \qquad (1)$$

In this formula, x1 represents an individual measurement while x¯ is the mean of all measurements within a sample. The number of sampled individuals is represented by n.

Mean given as:

$$\text{Mean } (\bar{x}) = \frac{\sum x}{n} \quad (2)$$

Table 3.1: Values obtained from each test and their standard deviations

	PR Interval (ms)	QRS Duration (ms)	P duration (ms)	Heart Rate (bpm)
Test 1	153	89	98	73
Test 2	158	86	102	70
Test 3	159	84	103	71
Mean±S.D	156.67±3.215	86.33±2.490	101±2.646	71.33±1.528

The values obtained for the standard deviation show that the precision of the device is good, hence it can be relied upon to give consistent measurements.

3.4.2. Test for Accuracy

It can be observed from the results above that the error for most of the tests is not significant however the means of the measurements provide a higher likelihood of avoiding the highest errors. Hence going forward the mean of at least 3 measurements can be relied upon as accurate and appropriate for diagnosis and referral.

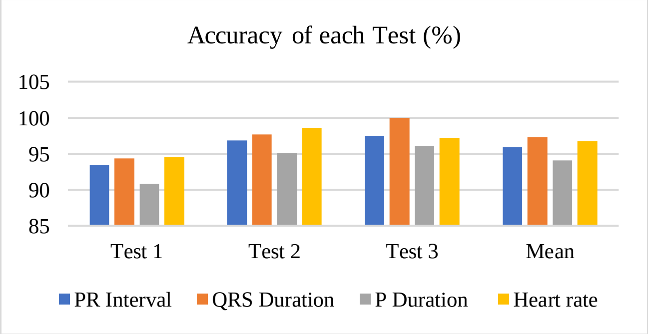

Figure 3.10: Chart showing the accuracy after each test and the mean

4. Conclusion

The ECG recorder prototype that was designed in this project is suitable for long-term monitoring, is affordable and has IoT capabilities for display and storage. The design consists of two alternative systems, an analog circuit, and a digital signal processing system to process the signal obtained from the electrodes. The analog circuit made up of resistors, capacitors, OpAmp, and other components formed amplifiers and filters which were used in processing the signal. The system was powered by a 3.7V Lithium-ion battery and the microcontroller employed was the ESP8266. The overall weight of the system was 37 grams which is light and a good weight for the user. The overall system was placed at the bottom of the shirt to help keep the shirt straight and in good form. An IoT architecture made up of Wi-Fi as the communication protocol and MQTT as the application transport protocol was used to send the electrocardiograph obtained from the system to an online platform for viewing and storage for future referral. The DSP system had two distinct features, the ability to process and filter the signal in real-time and the option to transfer the signal instantly to MATLAB for post-processing. Important information such as the heart rate, PR interval, QRS duration, and T interval were extracted and sent to the online dashboard to be used for diagnosis by a certified medical professional. Statistical analysis showed that the results obtained from the prototype were precise and accurate.

Acknowledgement

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