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Integrated Low-Cost Wearable Electrocardiograph System for Primary Assessment of Cases of Rural Residents †

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Abstract: In recent years, advances in both technology and medicine have made great progress. With the development of technology, low-cost and high-precision sensors have emerged and microcontrollers with high computing power and low power consumption have been created. In densely populated urban areas, health care is provided by a set of hospitals and medical centers where every patient can find an immediate response to their health concerns. However, medical care, particularly in non-urban areas, remains limited as many such areas do not have a hospital or medical center nearby. This results in inadequate medical care, both diagnostic and preventive, for the inhabitants of these areas. Today, the development of microprocessors, high-speed internet, and the low-cost sensors that have been developed can enable the creation of autonomous, accessible health monitoring units. In this work, an integrated low-cost, wearable electrocardiograph system is presented. The system is able to operate wherever there is an active internet connection. The proposed system consists of two parts. Firstly, the wearable ECG which can be located in the patient's home. Secondly, the information system, in which the data from wearable ECG are collected and visualized, so that the doctor has direct access to the patient's condition. Health is a precious commodity, and the application of technology is imperative, especially for the health care of citizens in remote areas.

Keywords: EGC; low-cost; IoT; remote monitoring; health care

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1. Introduction

According to the World Health Organization (WHO), cardiovascular disease (CVD) is the leading cause of death worldwide. An estimated 17.9 million people died from CVD in 2019, representing 32% of all deaths worldwide. Of these deaths, 85% were due to heart attack and stroke. Of the 17 million premature deaths (under age 70) from non-communicable diseases in 2019, 38% were due to CVD. Most cardiovascular diseases can be prevented by addressing behavioral and environmental risk factors such as smoking, unhealthy diet and obesity, lack of exercise, harmful use of alcohol, and air pollution. More than three-quarters of CVD deaths occur in low- and middle-income countries. It is important to identify cardiovascular disease as early as possible and initiate its management with counseling and medications [1]. The most common form of arrhythmia is atrial fibrillation, which represents a major medical challenge. Atrial fibrillation is associated with a high risk of cardiovascular events, including cardiovascular death, heart failure, ischemic heart disease, sudden cardiac death, and stroke [2]. Atrial fibrillation can be diagnosed by feeling the pulse but can be inaccurate due to increased heart rate. Therefore, it is most reliably diagnosed using electrocardiography (ECG).

It is important to identify cardiovascular disease as early as possible so that counseling and medical management can be initiated. The electrical activity of the heart is recorded by electrocardiography (ECG). The ECG signal is a bipolar low frequency weak signal and the normal excitation of the signal is 0.05–100 Hz [3]. Diagnosis from an ECG signal can help in various heart-related diseases. The recording of an electrocardiogram is carried out by placing electrodes in the patient's body, through which the electrical signals are received [4].

The research study in [5] presented the wireless ECG monitoring system using Raspberry pi as a development board and eHealth sensor platform. Their interconnection was performed with a connection board developed by Cooking Hacks. The data taken from the electrodes were sent to a database. The work in [6] presents a health monitoring system using IoT, based on Android, and specifically presents the necessary infrastructure such as microcontroller, communication protocols, and database management systems. A health monitoring system is presented by the work in [7], consisting of an ECG sensor and an accelerometer. The data were analyzed both to extract useful physiological parameters and to detect any abnormalities that may occur in each patient, as well as problems related to the heart. In [8], a low-power ECG monitoring system with wearable capability is presented. In detail, the design of a system with features, low-cost, wearability, and low power is presented. The ZigBee protocol was chosen for data transmission, and a low power ADC (ADS1246) from Texas Instruments was used. The paper in [9] presents a brief review of suitable components for building a portable ECG device, citing several companies that have successfully designed their own remote ECG monitoring systems. In [10], a five-module system for cardiac monitoring systems is proposed. The system includes body sensors, signal conditioners, analog to digital (ADC), and pressure converters. It also supports remote transmission and analysis, focusing on the use of mobile phones for monitoring, without the need for additional hardware, thus increasing ease of use.

In general, the structure of a wearable device includes a biosensor and a microcontroller module. Usually the microcontroller includes battery management, Wi-Fi transmission, etc. [11]. Regarding the sampling of an ECG signal, it is obvious that higher accuracy requires a higher sampling frequency. During the acquisition of the ECG signal, signal noise is also received, either from the contact of the electrodes with the body or from noise due to the power supply of other devices. These types of noises interfere with the signal and should be minimized [12]. The use of a filter is ideal for these cases. There are two types of filters: analog and digital. The choice of filter plays an important role in the quality of the resulting corrected signal [13]. Papers [14,15] present the implementation of an analog filter in ECG devices, which consist of passive elements: resistors, inductors, and capacitors. Digital filters give the possibility, as the correction of the signal is performed dynamically, of changing the parameters of the filter. This requires computational power and results in much better signal filtering. Digital filters in low-cost ECG devices are presented in [16–18]. Focusing on the energy efficiency of low-cost systems, according to the work of [19], this is achievable on affordable microcontrollers through a set of factors to be evaluated during implementation.

Following our work [20], as a continuation of our research efforts, this paper presents an integrated, low-cost, ECG monitoring system. The proposed system consists of a wearable ECG monitoring device and an information system. The portable device consists of a low-cost microcontroller which supports wireless networking for data transmission and a low-cost ECG sensor. This system can be placed inside health centers in remote areas or even in the patient's home. The information system is used to collect, store, and visualize the data. In addition, the filtering of the signal with a digital filter was implemented and the results were satisfactory. With the proposed system, the doctor can remotely access the ECG of a patient.

The article is structured as follows: Section 2 presents the Materials and Methods; Section 3 covers the Results and Discussion; and Section 4 presents the Conclusions.

2. Materials and Methods

2.1. ECG Characteristic Analysis

Figure 1 describes a fairly typical ECG signal [21]. Three features of the waveform can be distinguished: the P signal, the QRS signal complex, and the T signal. The P signal is associated with atrial activation, the QRS signal complex with ventricular activation, and the T signal with ventricular repolarization.

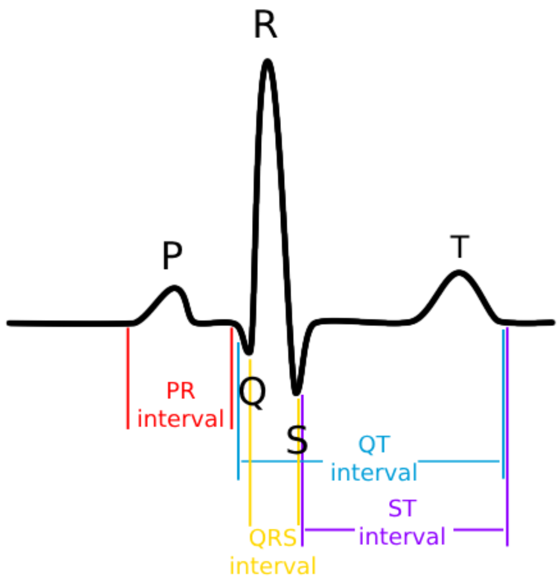


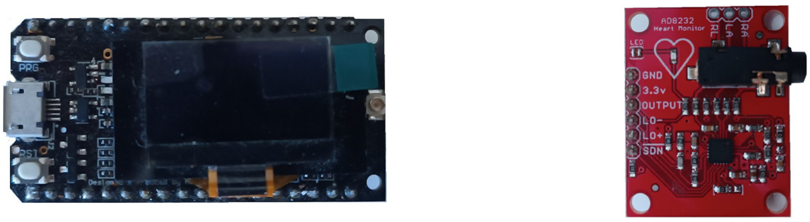
Figure 1. Typical ECG signal [21].

In Figure 1, the electrocardiogram intervals are depicted. The times between P, Q, R, S, and T points and their width are important factors for the diagnosis by the doctor. The first interval (PR) is the duration from the beginning of the P signal to the beginning of the Q signal. The second interval (QRS) is the duration from the beginning of the Q signal to the end of the S signal, i.e., the duration of the total QRS signal. The third interval (QT) is the duration from the beginning of the Q signal to the end of the T signal, i.e., it includes the total QRS signal and the T signal. The fourth interval (ST) is the duration of the S signal to the end of the T signal. The fifth interval (RR) is the duration from the peak of a wave R to the peak of the next wave R.

2.2. Design and Implementation of a Wearable ECG Device

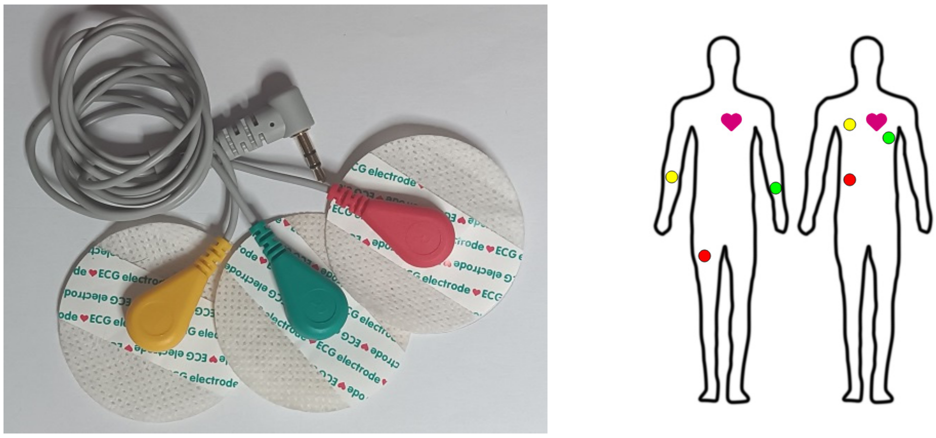
This study presents the implementation of a low-cost portable ECG monitoring station. The data transmission is conducted via a wireless network (Wi-Fi). Each station consists of a microcontroller and an ECG sensor. The microcontroller chosen is the affordable TTGO@ESP32 (Shenzhen, China) [22] (Figure 2a). It can cover the computing power required by the proposed ECG monitoring station. Also, can provide a large number of analog and digital ports, as well as communication protocols (UART, SPI, and I2C) and wireless networking (Wi-Fi). The affordable and low-power Single-Lead, Heart Rate Monitor Front End sensor AD8232 (SparkFun Electronics, Dry Creek Pkwy, Niwot, CO, USA) from Analog Devices was chosen as the ECG sensor [23] (Figure 2b).

The electrodes of the AD8232 sensor (Figure 3a) are placed in specific positions on the body [24], as shown in Figure 3b. Regarding the wearability of the sensor's electrodes on the human body, a section of fabric was used on which the electrodes are placed at the appropriate points. The fabric on one side is placed on the shoulder and wrapped around the human body while the other side is attached by hook-and-loop fasteners to the fabric.



(**a**) (**b**)

Figure 2. The parts of low-cost ECG device: (**a**) TTGO@ESP32 microcontroller; (**b**) AD8232 ECG sensor.



(**a**) (**b**)

Figure 3. Sensor's electrodes and electrodes placement: (**a**) set of three electrodes of low-cost ECG sensor [24]; (**b**) two possible locations of the three electrodes (red, green, and yellow dots) on the human body [24].

To achieve the portability of the device, a small form factor plastic box (110 mm × 60 mm × 30 mm) was used, while powering the device is possible even with a mobile phone charger (micro USB-5 volt). The final composition of the low-cost electrocardiograph with all its components (microcontroller, ECG sensor, and sensor electrodes), is shown in Figure 4.

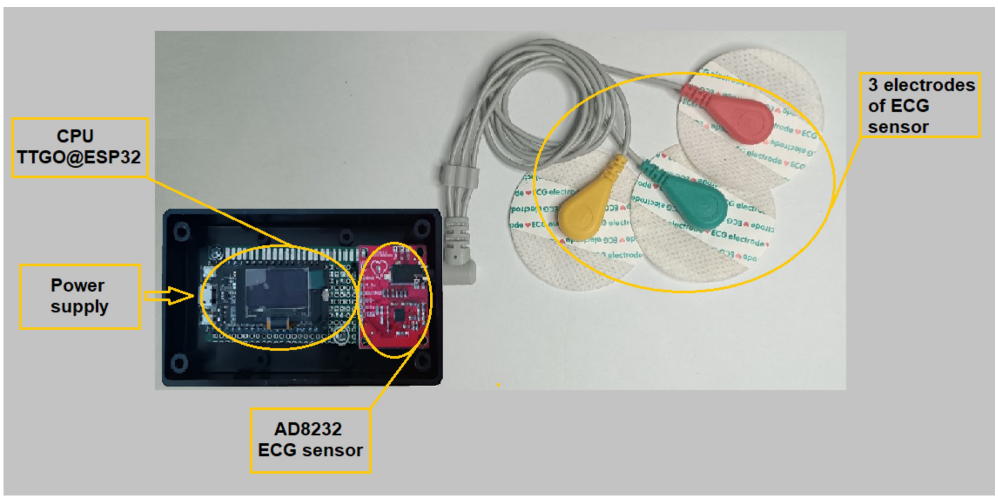


Figure 4. The complete construction of the low-cost electrocardiograph.

2.3. Design and Implementation of an Information System for the Collection and Visualization of ECG Data

The information system is based on an open-source operating system (based on Linux), while two open-source server applications are running on it. The first server supports an open-source database specifically designed for time series data, while the other server supports web-based software for data visualization.

The use of open-source software is preferred against proprietary software because it allows the source code to be adapted according to the requirements of the any implementation from the community. It also encourages participation and contribution by members of the community and researchers. In our work, InfluxDB v2.7.10 [25] was chosen because it is designed strictly for time series data. InfluxDB presents similarities to SQL database but is very different in functionality in many perspectives. It is designed to manage and store large volumes of time series data, while quickly performing real-time analysis. InfluxDB stores data in so-called buckets. Data in buckets can be distinguished based on timestamp and/or tags associated with each point in time uniquely. This is like a SQL database table where the primary key is predefined by the system and is always time.

Data visualization for the end user is conducted through a web page on the internet, using the Grafana lab software v9.5.2 [26]. Grafana is an open-source software which, in addition to visualization, performs data analysis with the help of customizable dashboards. Grafana can connect to various databases like Prometheus, Influx DB, MySQL, etc. The open configuration environment of this software allows the implementation of custom plugins to connect to any data source of choice. From the Grafana environment the user has the possibility to monitor, study, and analyze the data. In addition, it is possible to monitor the data for a specific time period, which makes the process of time series analysis easy. In general, this software provides a user-friendly management interface, in which the user can create control panels and can perform processes with various measurement tools included in the application. In addition, in Grafana software users are divided into roles such as "administrator", "operator", and "viewer", where each role has defined access/use rights, thus controlling the ability of each user to change the data, as well as the confidentiality of the data and its dissemination to third parties. Finally, with regard to security in terms of data transmission, it is clarified that, in all cases, both the connection of the measuring device to the database and the connection of the database to the visualization software, unique API keys were used for each connection.

3. Results and Discussion

According to the operation of the software inside the microcontroller, a packet with measurements is created. Every packet is about eight seconds long. Each point (measurement) inside that packet, is acquired with an interval of 500 microseconds apart.

A total of 16,384 measurements are taken. The package of measurements is then formatted appropriately and sent to the database via Wi-Fi.

The raw data of the measurements are shown in Figure 5. It can be noticed that the cardiogram contains a lot of signal noise in respect to Figure 1. This results in a not easily recognizable diagram. The periods of the signal as depicted from Figure 1 are not distinguished easily.

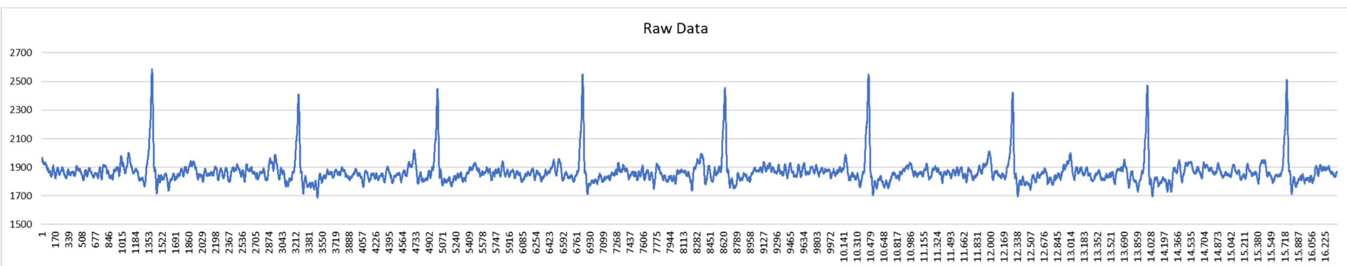


Figure 5. Primary measurements of low-cost ECG.

For both research and evaluation purposes, the moving average method was applied in different interval values.

The figures below show the results for different intervals. Figures 6–8 show the corrected signal with intervals of 50, 100, and 200 points, respectively.

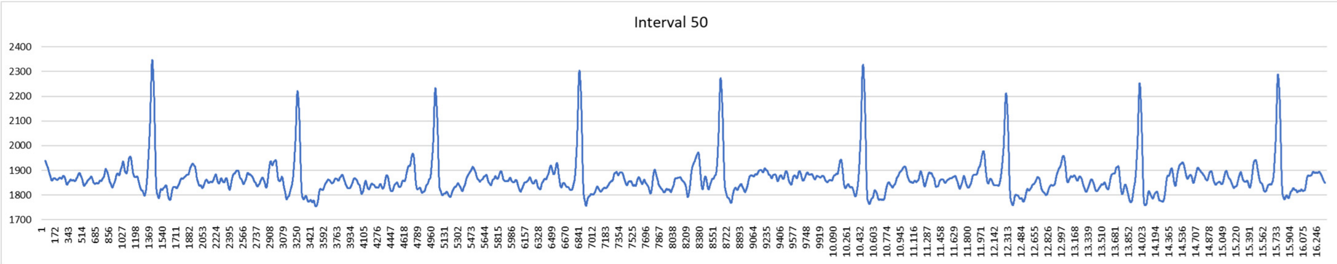


Figure 6. Corrected measurements by moving average method (Interval = 50 points).

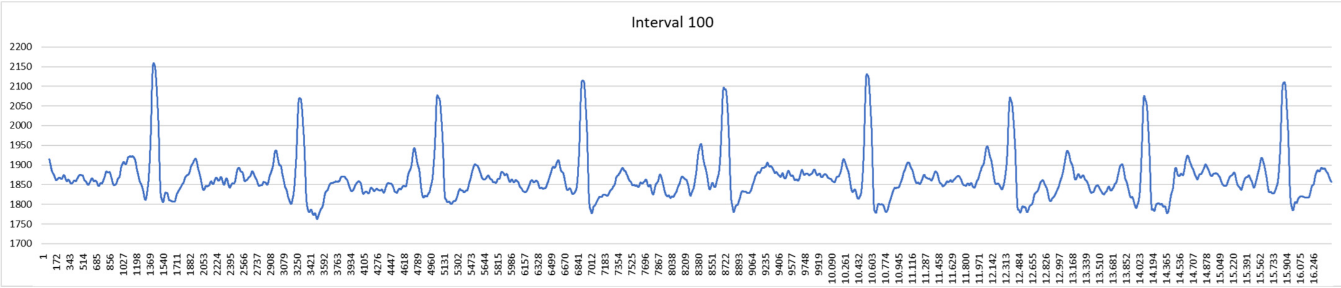


Figure 7. Corrected measurements by moving average method (Interval = 100 points).

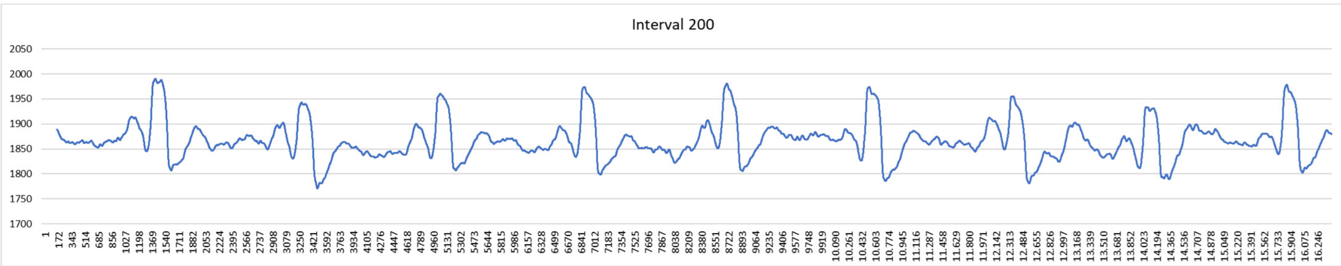


Figure 8. Corrected measurements by moving average method (Interval = 200 points).

Observing Figures 6–8, it is obvious that the signal is more distinct in Figure 7 where the interval value of the moving average method is 100 points, compared to Figures 6 and 8, where in Figure 6 (interval value 50 points) the noise is evident, while in Figure 8 (interval value 200 points), the signal distortion is clearly visible. In Figure 9, a time section of Figure 7 is shown to illustrate the specific points P, Q, R, S, and T of the cardiogram.

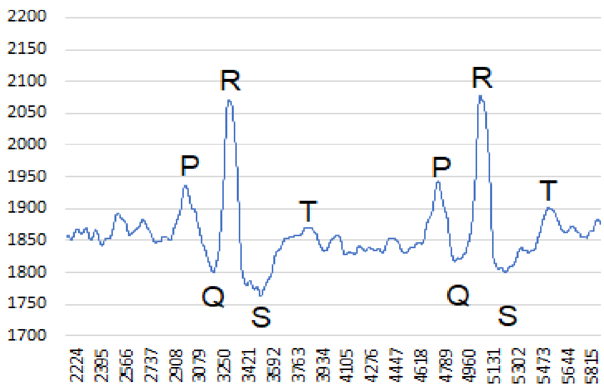


Figure 9. Time section of corrected measurements and P, Q, R, S, and T points.

Through the web-based Grafana software, a doctor can see the results of the measurement as shown in Figure 10. For the purposes of the experiment, both data, raw and the corrected measurements, are shown in this Figure.

Figure 10. Grafana, ECG measurements dashboard.

More specifically, Figure 11 shows the raw measurements, with the noise clearly in place, distorting the observable signal. Figure 12 shows the corrected measurements using the moving average method, where the noise reduction is evident.

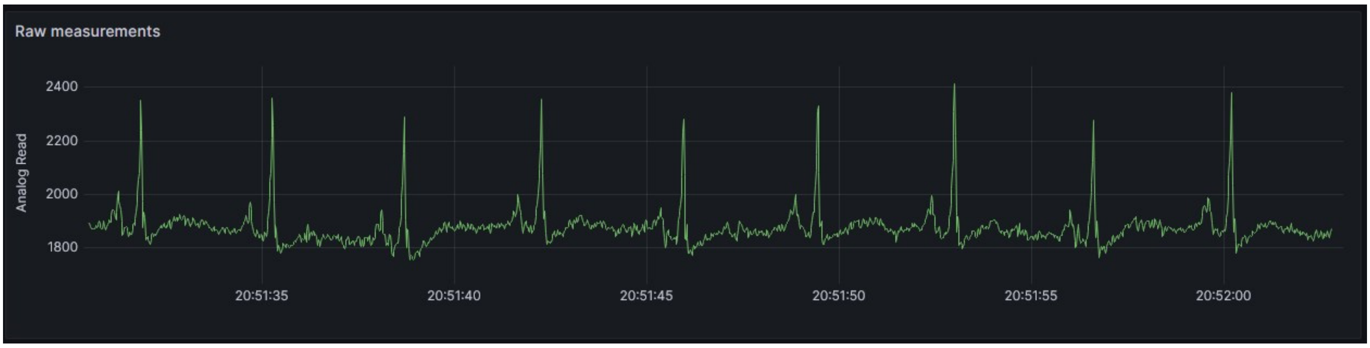


Figure 11. Grafana, low-cost ECG Raw measurements, panel.

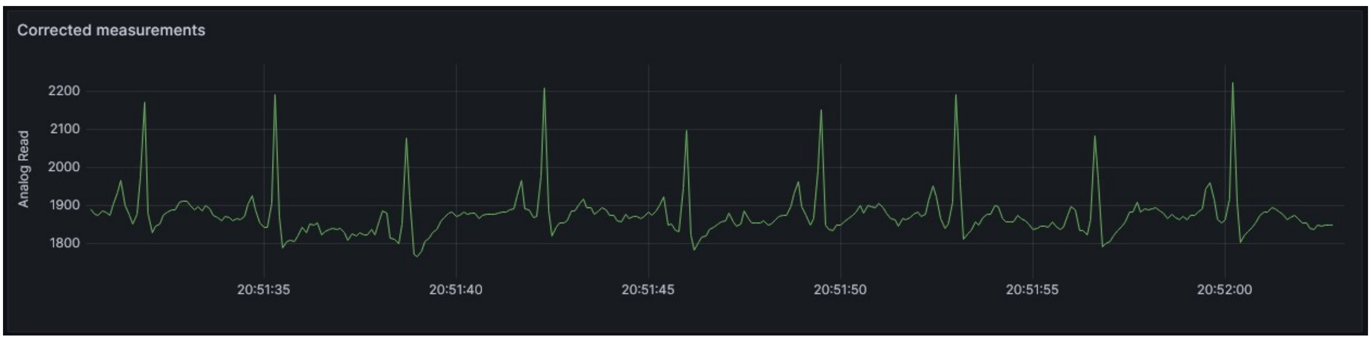


Figure 12. Grafana, low-cost ECG Corrected measurements, panel.

The overall results are of particular interest, as the aim of this work is to demonstrate the usefulness of a low-cost ECG system, especially in the health sector. Obviously, this system cannot replace professionally calibrated cardiograph devices, but it can be used as a first step of diagnosis by the doctor, remotely, for people who live in remote areas and areas where health services are not at a short distance. Since we are referring to low-cost sensors, it is understood that the quality of the measurements will not be excellent. This is also evident from the raw measurements according to Figure 11. The solution to this problem is by using the moving average method where the result is shown in Figure 12. This method, despite its simplicity, is proven to be quite satisfactory. Figure 12 also depicts the points P, Q, R, S, and T, which for the doctor are of critical importance for the interpretation of the cardiogram.

4. Conclusions

Health is a common good for all, and it is imperative that technology contributes to the field of medicine with the aim of medical prevention.

This work presents an integrated low-cost electrocardiograph system, consisting of a measurement device and an information system. The aim is to enable the doctor to monitor the patient's electrocardiogram remotely. Obviously, the proposed system cannot replace professional systems, but the application of the system can be used as a first diagnostic tool for people living in remote areas.

The proposed system and the methodology followed demonstrate excellent results, as it works in real time, while the correction of the signal from the noise resulted in the emergence of important and necessary parameters according to which the doctor can interpret the cardiogram. Low-cost systems (CPU, sensors) can be used in a wide range of applications for human service. Their application in the field of health is an area of research, and the development of such applications and systems can be used as a first step in diagnosis, which can save lives. Further testing in such systems and especially using open-source software, may advance this type of field greatly and in less time.

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Conflicts of Interest: The authors declare no conflicts of interest.

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