Electrocardiograph (ECG) Circuit Design and Software-based Processing using LabVIEW

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Abstract—The efficiency and acquisition of a clean (diagnosable) ECG signal dependent upon the proper selection of electronic components and the techniques used for noise elimination. Given that the human body and the lead cables act as antennas, hence picking up noises from the surroundings, thus a major part in the design of an ECG device is to apply various techniques for noise reduction at the early stage of the transmission and processing of the signal. This paper, therefore, covers the design and development of a Single Chanel 3-Lead Electrocardiograph and a Software-based processing environment. Main design characteristics include reduction of common mode voltages, good protection for the patient, use of the ECG device for both monitoring and automatic extraction (measurements) of the ECG components by the software. The hardware consisted of a lead selection stage for the user to select the bipolar lead for recording, a pre-amplification stage for amplifying the differential potentials while rejecting common mode voltages, an electrical isolation stage from three filtering stages with different bandwidths for noise attenuation, a power line interference reduction stage and a final amplification stage. A program in LabVIEW was developed to further improve the quality of the ECG signal, extract all its features and automatically calculate the main ECG output waveforms. The program had two main sections: The filtering section for removing power line interference, wideband noises and baseline wandering, and the analysis section for automatically extracting and measuring all the features of the ECG in real time. A Front Panel Environment was, therefore, developed for the user interface. The present system produced ECG tracings without the influence of noise/artefacts and provided accurate detection and measurement of all the components of the ECG signal.

Index Terms—ECG Circuit Design; Noise Elimination; LabVIEW Processing; ECG Component Measurements.

I. INTRODUCTION

Electrocardiography (ECG) is the most commonly conducted diagnostic technique for detecting heart's electrical activity via electrodes/receivers attached to body surface which produces a graphical tracing known as Electrocardiogram. The intrinsic electrical activity and conductivity of the heart are due to the generation of electrical impulses by the sinoatrial node (natural pacemaker) and depolarisation and repolarisation of the cardiac cells. ECG is, therefore, an electrophysiological measurement which is non-invasive and able to detect normal and abnormal activities of the heart. Electrical impulses produced by the cardiac cells spread within the heart's conduction pathways causing the heart to contract and pump blood to the rest of the body. During the cardiac cycle and for each contraction, a spatio-temporal electric field is generated through the anatomically complex volume conductor of the thorax and abdomen to the skin where a spatio-temporal potential difference can be measured [1]. The electrical impulses on the body surface are characterised by an extremely weak signal at a range of 0.5 to 5mV with a maximum frequency content of 125Hz [2] which are highly vulnerable to a variety of disturbances. The amplitude of the ECG waves and their shape may differ depending on the location of the electrode pair on the body surface. The potential differences can be detected by placing electrodes on precise locations on the body surface and extracted via lead cables into the pre-amplification stage where they are amplified while common mode voltages are rejected. ECG devices most commonly provide an overall amplification with a gain of about 1000 and in a specific bandwidth of frequencies. In order to bring the ECG signal to its final diagnosable form, further processing of the signal through filtering and amplification stages are necessary in order to eliminate unwanted interfering signals which degrade the quality of the desirable ECG signal.

The recorded ECG signals are influenced by a variety of noises and artefacts that are within the bandwidth of interest. Extracting useful information from the noisy potentials, the raw ECG signals have to be processed which involves mainly two stages. The first stage is the pre-processing stage for attenuation and removing the disturbances from the recorded noisy ECG signals. The second stage is the feature extraction stage during which all the features of the ECG signal are extracted and analysed further.

Given that the human body acts as a huge antenna that picks up noises from the surroundings, a major part in the design of an ECG device is noise reduction in order to achieve a clean graphic tracing of the heart's electrical activity from which all the ECG features are fully extracted and visible for diagnosis. Main sources of noise are due to common mode voltages with high amplitudes that can mask the extremely weak ECG signal and saturate the amplifiers. Some of the interferences are really harmful to the ECG signal and cannot be totally eliminated. Mains hum and artefacts which interfere with the ECG waveform degrade the ECG tracing, thus, making a diagnosis of possible cardiac disorders extremely difficult. Main sources of noise include 50Hz electric field interference due to power mains, motion artefacts, electromagnetic interference, dc potentials, muscle contraction and high-frequency interference caused by nearby electronic equipment. In addition, inaccurate selection

of electronic components, especially the instrumentation and operational amplifiers, which are not capable of dealing with the characteristics of such bio-signals in the presence of common mode voltages will lead to no extraction or to a degraded ECG signal [3].

This work, therefore, aimed to design and manufacture a single channel 3-Lead ECG device capable of dealing with the characteristics of the ECG signal and producing real-time ECG tracings without the influence of noises and interferences. Development of a software-based processing environment also took place for further processing, i.e. for improving the quality of the ECG signal acquired from the hardware and for automatically extracting and calculating all the main features of the ECG. Since the ECG signals are characterised by high source impedance, weak amplitude and highly vulnerable to a variety of noises, the ECG hardware must be able to deal with these characteristics and detect the electrical potentials from the body surface, amplify them, remove common mode interfering signals and interface with the PC/laptop for real-time analysis. Basically, the hardware

consists of a lead selection stage, a front-end instrumentation amplifier, a right leg driver, an isolation amplifier, filtering and amplification stages. The software-based processing environment consists of the programming environment which includes the digital filters for further improving the quality of the signal and eliminating baseline wanders, detecting and measuring all the components of the ECG signal via the function and from the Graphical User Environment where the ECG tracing is displayed with the automatic calculation of the main ECG components.

A typical ECG tracing is shown in Figure 1, characterised by three upward waves labelled as P, QRS, and T waves, representing the sequence of depolarisation (atria contraction as P wave followed by ventricular contraction as QRS wave) and repolarisation of the ventricles (T wave). Therefore, a normal ECG tracing comprises of an initial upward P wave always followed by the QRS complex and then a T wave. Atria repolarisation (relaxation) is weak and masked by QRS. The straight line (zero voltage) on the ECG tracing represents the baseline known as the isoelectric line.
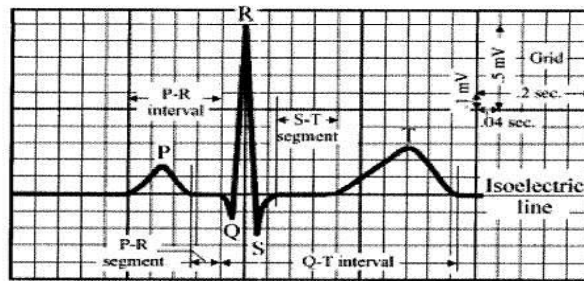

Figure 1: Typical (Normal) ECG Tracing

The following is a summary of the expected values for ECG waves and parameters used as a guide to understand the ECG recordings [4]:

P Wave: The P wave results from atria contraction (or depolarization). P wave is generally about 1 box (0.04sec) wide or 1 box tall (0.1mV). P wave that exceeds these values might indicate atria hypertrophy, i.e. enlargement.
PR Interval: The PR interval is measured from the start of the P wave to the start of Q wave. It represents the duration of **atria depolarization (contraction)**. Regular duration is from **0.12 to 0.20 seconds, about 3 to 5 box wide.** If the PR interval is greater than 0.20 seconds, then an AV block might be present.
QRS Complex: The QRS complex is measured from the start of Q wave to the end of S wave. It represents the duration of **ventricle depolarization (contraction)**. Regular duration is from **0.08 – 0.12 seconds, about 2 to 3 box wide**. If the duration is longer, it might indicate the presence of bundle branch blocks.
QT/QTc: The QT/QTc is measured from the start of the Q wave to the end of T wave. QT interval represents the duration of **contraction and relaxation of the ventricles**. This duration varies inversely with the heart rate. The regular QTc is approximately **0.41** seconds for an accurate measurement, it is corrected with the heart rate with the following formula to get QTc:

$$QTc = QT + 1.75 \ (HR - 60)$$

ST Segment: The ST segment is measured by end of S wave, J point, to the start of T wave. This segment is important in identifying pathologies such as myocardial infarctions (heart attacks) and ischemia (oxygen deprivation).

II. ECG CIRCUIT DESIGN AND CONSTRUCTION

Due to the characteristics of the ECG signal and the appearance of common mode interfering signals degrading the quality of the ECG signal, there are some major requirements for the ECG circuit design as listed [5]:

  i.   The device should be able to deal with weak differential potentials in the range of 0.5mV to 5mV plus the dc components and the common mode voltages.
 ii.   The device should be able to detect the weak ionic current from the body surface and convert it into an electrical signal in order to be processed further.
iii.   The device should be able to transmit the differential potentials into the first stage of the hardware with minimum possible noise.
 iv.   The device should contain a Lead selector stage from which the user is able to select which bipolar Lead to record each time.
  v.   The front-end amplifier of the device should be able to amplify sufficiently the ECG signal while rejecting common mode voltages by having a high Common Mode Rejection Ratio (CMRR) above 100db.
 vi.   The device should not allow leakage currents greater than 10μA to flow through the patient.

vii. The device must provide electrical isolation and protect the patient from electrical shock.

viii. The instrument should have an overall gain of about 1000 in order for the signal to be strong enough to be transmitted to the PC.

ix. The instrument should provide sufficiently correct filtering stages for eliminating unwanted interferences and dc components.

x. The device should have different bandwidth stages so that to be used for both clinical and monitoring recordings.

- It should have a stage with a bandwidth of 0.03 to 100Hz for clinical applications.
- 10.2 It should have a stage with a bandwidth of 0.03 to 50Hz for the monitoring applications.

xi. The device should be battery powered for more protection of the patient.

xii. The hardware should be able to interface with the PC.

III. BLOCK DIAGRAM OF THE WHOLE ECD DEVICE

In this work, a single channel 3-Lead Electrocardiograph was successfully designed and tested with all the stages as shown in Figure 2. The main function of the ECG hardware is to detect the electrical potentials from the body surface, transmit them into the pre-amplification stage of the circuit for amplification followed by common mode voltage rejection, filtering of any unwanted low and high frequency signals that may interfere with the desirable ECG signal, setting the required bandwidths for monitoring, ECG recordings and amplifying the filtered ECG signal further to be sufficiently strong for transmission to the PC via Data Acquisition (DAQ) for final monitoring and analysis of the recordings [6].
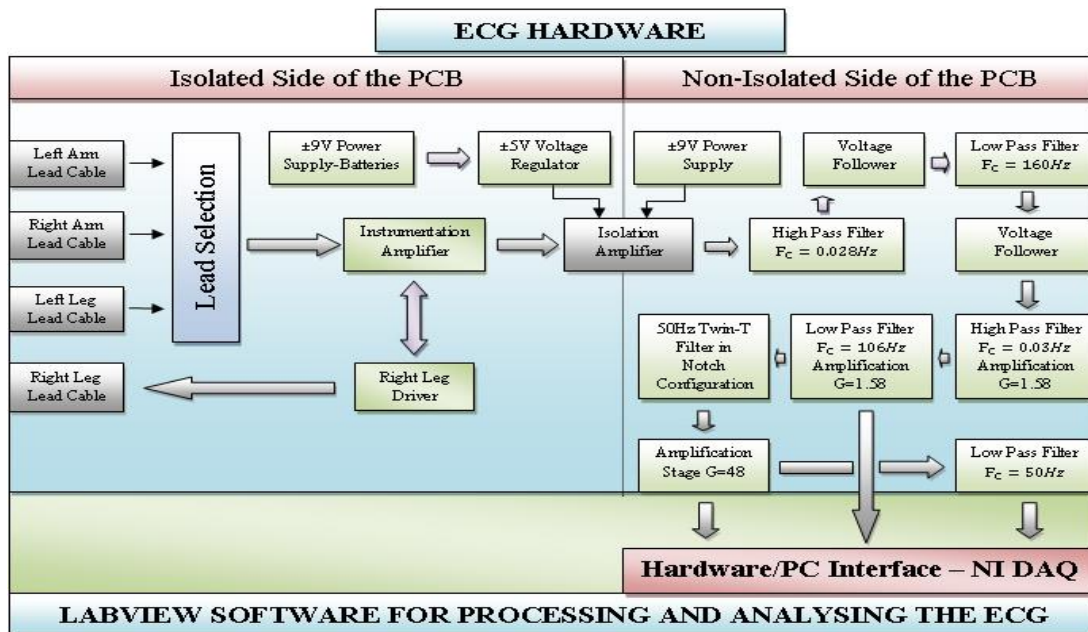

Figure 2: Block Diagram of the ECG hardware

Considering the block diagram shown in Figure 2, the hardware is separated into two sides, the isolated side and the non-isolated side due to the inclusion of an isolation amplifier which offers protection to the patient from electrical shock. The isolated side which is in contact with the patient consists of two main stages: The lead selection stage for selecting which lead to record and the pre-amplification stage for amplifying the signal and rejecting common mode voltages. The isolated side is powered by ±5V dual supply delivered from two 9V batteries connected in series for achieving a ±9V dual supply at its ends and regulated to ±5V by two ±5V voltage regulators. Four electrodes are attached to the patient's upper and lower limbs and four lead cables are used to connect the patient to the isolated front-end of the hardware for transmitting the signal into the lead selection stage. The three electrodes attached to the patient's Left arm (LA), Right arm (RA) and Left leg (LL) are used for detecting the ionic current from the body surface and converting into an electrical signal and the fourth electrode is attached to the Right leg (RL) and via lead cable to the output of the right leg driver used as the reference electrode in order to measure the potential difference between a pair of three electrodes $(V_{L_A}, V_{R_A}, V_{L_L})$. The differential potentials are then transmitted into the lead selection stage from which the user can choose via switches leading to recording. As the switch is turned on the differential potentials plus common mode voltages and dc potentials are transmitted into the differential inputs of the instrumentation amplifier which amplifies the differential potentials while it rejects common mode voltages. At the same time, the right leg driver circuit detects and receives an average of the common mode voltages and sends them back to the right leg of the patient eliminating in this way common mode voltages to be further amplified and processed by the device. The isolation amplifier is used for patient protection in case something goes wrong in the non-isolated side which is in contact with the PC not allowing any leakage current to flow backwards to the body of the patient.

The non-isolated side of the circuit is powered by a ±9V dual supply delivered by two 9 volt batteries. The non-isolated side consists of 5 stages for further processing the ECG signal. The first stage right after the isolation amplifier consists of a high and low pass filters for filtering any unwanted low and high-frequency components and setting the first bandwidth of the hardware. In this stage, a 1st order active high pass filter with a lower cutoff frequency of 0.028Hz is used and placed as close as possible to the pre-

amplification stage for eliminating low-frequency components and dc potentials below its cutoff frequency created due to electrode potentials. Right after the high pass filter, a 2nd order active low pass filter with a high cutoff frequency of 160Hz is used to eliminate high unwanted frequency components above its cutoff frequency and set to the higher frequency of the circuit's bandwidth. At this stage, a bandwidth of 0.028Hz to 160Hz is created which can be used for ECG recordings.

Furthermore, the second stage of the non-isolated side is composed of a 2nd order Sallen & Key Butterworth high pass filter with low cutoff frequency of 0.03Hz for further attenuating dc components and a 3rd order Sallen & Key Butterworth low pass filter with high cutoff frequency of 106Hz for further eliminating unwanted high frequency signals and setting the high cutoff frequency of the second bandwidth of the circuit. In addition to filtering, this stage is used to give a small enhancement to the signal with a gain of 1.58 set by the two op-amps which compose the active filters. At this stage, the second bandwidth of 0.03Hz to 106Hz is created and used for ECG recordings where all the components of the ECG are left intact.

The third stage of the non-isolated side includes a Twin-T 50Hz Notch filter which is used to attenuate as much as possible the most harmful interference to the ECG signal, i.e. that of the 50Hz electric field. This stage allows all the ranges of frequencies set by the previous filters to pass through to its output except that of 50Hz. This means that only 50Hz interfering signals will be stopped and eliminated at this stage leaving all the components of the ECG signal intact for further processing. The fourth stage of the non-isolated side includes a final amplification stage for giving the final enhancement to the signal in order to be strong enough to be transmitted to the PC for analysis. The gain of the amplifier is set to 47 in order to achieve an overall gain of about 1000. The last stage includes a 2nd order low pass filter with a high cutoff frequency above 50Hz which further eliminates unwanted high frequencies and it is used to set the third and final bandwidth of the circuit that can be used for monitoring applications according to the requirements of this work.

The hardware to PC interface is achieved with the use of DAQ which sends the amplified and filtered ECG signal to the PC was LabVIEW software is used and programmed for further processing, displaying and analysing the ECG signal. The programming of the software includes the use of digital filters for improving the quality of the signal, wavelet functions and denoising the signal, functions for peaks and valleys detection, and functions for measuring and displaying all the components of the ECG automatically including the heart rate. Figure 3 illustrates the block diagram of the ECG device functioning as a whole including the software-based processing and analysis of the ECG signal.
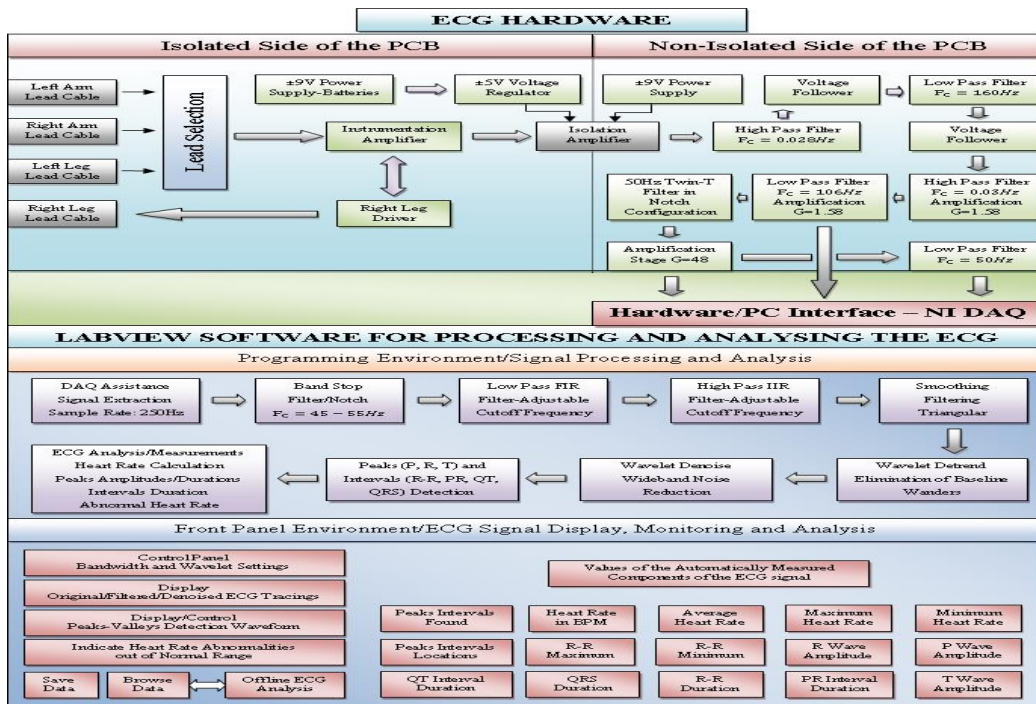

Figure 3: Block Diagram of the whole ECG device including the software processing stage

IV. OVERALL SCHEMATIC DIAGRAM OF THE ECG HARDWARE

Each stage of the circuit was designed and tested theoretically using Proteus Simulator and thus all the stages were combined to function together for the processing of the ECG signal. To test theoretically the function of each stage and the circuit as a whole, a virtual signal generator was used in order to apply known differential voltages plus interfering signals to the inputs of the instrumentation amplifier. This allowed comparing the output of each stage with theoretical calculations and the expected values so as to obtain the proper function of the circuit. The schematic diagram of the overall combined ECG circuit is shown in Figure 4.
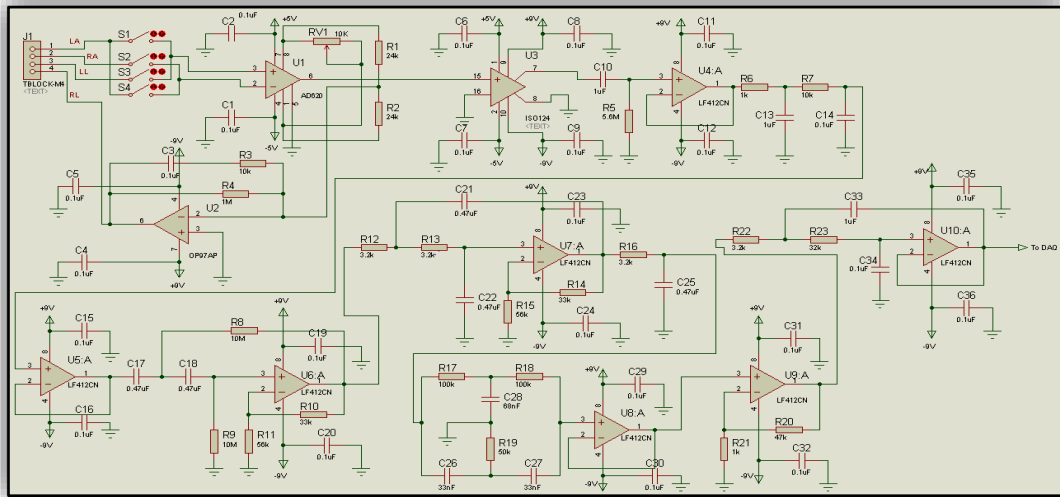
Figure 4: Schematic Diagram of the overall combined ECG circuit

The overall function of the circuit is to process the ECG signal through amplification and filtering stages with interference attenuation to provide protection to the patient and to generate accurate and diagnosable ECG tracings using the standard bipolar leads. The circuit for patient protection is separated into two sides by the isolation amplifier, with the front side connected to the patient to be the isolated side and the rest of the circuit connected to the PC to be the non-isolated side. The electrical potentials detected from the body surface are transmitted via lead cables to the Lead selection stage composed of a switch-network for selecting which bipolar lead to record at a time. Once the lead is selected, the differential potential is transmitted to the differential inputs of the instrumentation amplifier which amplifies the signal through an adjustable gain while rejecting common mode voltages due to its high CMRR properties. At the same time, an average of the common mode voltages is fed into the right leg driver which inverts the common interfering signals, amplifies them and feeds them back to the patient's right leg eliminating in this way unwanted interfering signals. The ECG signal is then transmitted to the input section of the isolation amplifier which modulates the signal and passes it to its output section through a capacitive barrier where it is converted back to its normal form and transmitted to the non-isolated side of the circuit. The ECG signal is then passed through the first filtering stage with a bandwidth of 0.028Hz to 160Hz where dc components and high-frequency interfering signals are eliminated.

Right after the first filtering of the signal, a second filtering stage with bandwidth 0.03Hz to 106Hz and overall pass-band gain of 2.50, provides more attenuation to the dc components and high frequency interfering signals and gives a small enhancement to the signal. The bandwidth of this stage is selected to comply with AAMI standards for clinical ECG bandwidth. The signal is then further processed through a Twin-T 50Hz Notch filter for cancelling 50Hz electric field interference and transmitted into the final amplification of the circuit with a fixed gain of 48 for amplifying the signal in order to be sufficiently strong for transmission to the PC.

Before the signal is transferred to the PC for monitoring, a third filtering stage is used with a high cutoff frequency above 50Hz for further attenuating unwanted high frequency interfering signals which creates a bandwidth of 0.03Hz to 50Hz which can be used for monitoring applications. With this configuration, the user can choose from the three different bandwidths which one to use depending on the application. The three bandwidths offered by the ECG hardware are as follows:

  i. Clinical ECG: 0.028Hz-160Hz.
  ii. Clinical ECG: 0.03Hz-106Hz.
  iii. Monitoring ECG: 0.03Hz-50Hz.

The overall gain of the ECG circuit is 1196 or 61.5dB (20log (g)) and is calculated by multiplying the gain of each of the individual stages as follows:

$$G_O = G_1 \times G_2 \times G_2 \times G_4$$
$$G_O = 9.98 \times 1.58 \times 1.58 \times 48$$
$$\mathbf{G_O = 1196}$$

V. PRACTICAL DESIGN AND CONSTRUCTION OF THE ECG CIRCUIT

Four coaxial cables were used in order to build the lead cables for transmitting the ECG signal from the electrodes to the input of the lead selection stage. The inner copper wires of all four cables were soldered on to the alligator clips in order to easily attach them to the electrodes while their braided shields were twisted together to achieve common shield.

Following the overall schematic diagram that is given in Figure 4, all the electronic components were assembled on a stripboard as shown in Figure 5. The whole practical procedure included a step by step construction and testing of the circuit where the output for each of the constructed stage was tested before constructing the next stage ensuring the appropriate performance of each stage.
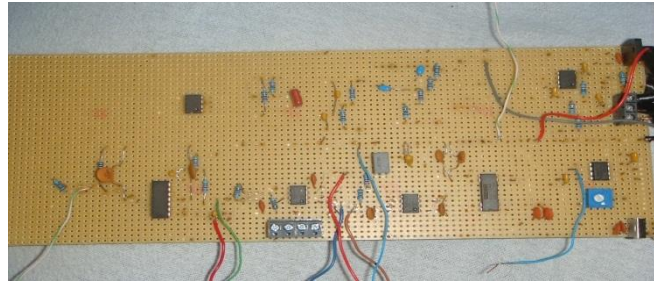
Figure 5: Constructed ECG circuit

Considering Figure 5, the right side of the circuit is the isolated side which contains the lead selection stage, the instrumentation amplifier and the right leg driver. The positive and negative voltage regulators were placed at the top and bottom ends of the stripboard, respectively, from which the ±5V dual supply is delivered which supplies the active components of the isolated side. The two 9V batteries were placed within a battery holder so that from its terminals a ±9V dual supply is delivered to the circuit while its common terminal provides the ground for the circuit.

Apart from the techniques used to achieve electrical isolation, a physical barrier was created between the isolated and the non-isolated sides of the circuit by simply removing the copper strips ensuring in this way a complete isolation of the two sides. The four-way connector in the middle of the circuit is used to connect the outputs of the three different filtering stages and further connected to the analogue inputs of the DAQ. Before testing the function of the circuit, fault tests were performed based on the algorithm shown in Figure 6 which was created in order to make corrections needed and to ensure the proper performance of the circuit.
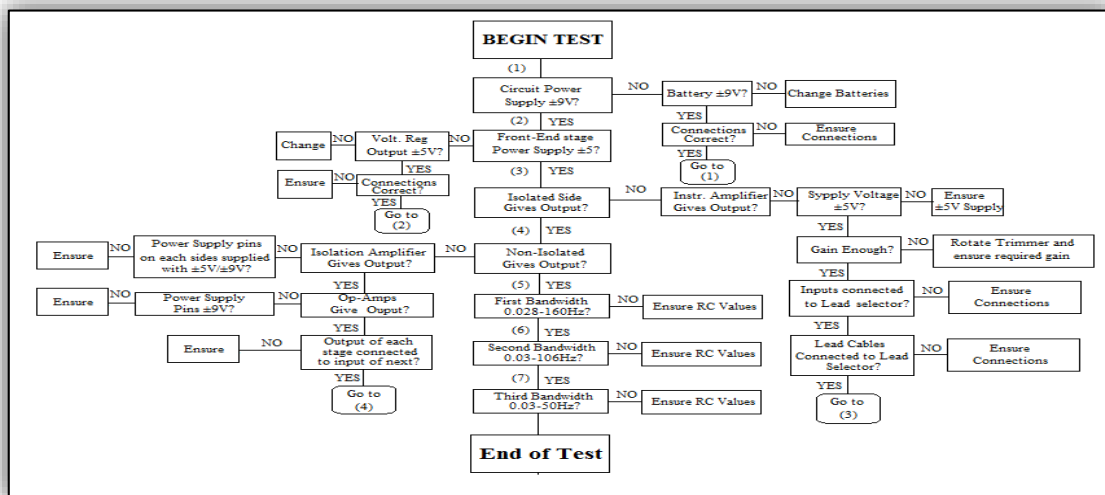

Figure 6: Fault detection algorithm

Having constructed the ECG hardware, the frequency responses of each of the filtering stages were obtained using LabVIEW. The frequency response graph will show the filter's output spectrum in response to the input signal.

VI. DEVELOPMENT OF THE SOFTWARE-BASED ENVIRONMENT

Extracting and analysing the features of the ECG signal initially requires the pre-processing of the signal for removing unnecessary signals and disturbances. Despite the pre-processing of the signal by the hardware, some disturbances do still exist and disturb the output signal which has to be totally removed in order to accurately extract and analyse all the ECG features. Disturbances such as power line interference, baseline wandering and other wideband noises can be totally removed by the software before analysing the ECG signal. The major requirements for the software processing and analysis of the ECG signal are listed:

i. The software should be able to remove power line interference, baseline wandering and other wideband noises.
ii. The software should be able to detect and extract all the features of the ECG signal.
iii. The software should be able to automatically measure and calculate all the components of the ECG signal.
iv. The software should be able to provide real-time and offline ECG signal analysis.
v. The software should be able to detect Heart Rate abnormalities.
vi. The software should provide a front panel environment so that the user will be able to:
    a. Control the bandwidth of the filters and apply the necessary settings.
    b. View and monitor all the ECG signals in real time.
    c. Indicate all the automatically measured and calculated features of the ECG signal.
    d. Indicate Heart Rate abnormalities.
    e. Save the ECG data.

f. Read the saved ECG data.
g. Apply offline ECG analysis.

VII.   FLOWCHART OF THE OVERALL SOFTWARE ENVIRONMENT FOR PROCESSING AND ANALYZING THE ECG SIGNALS

Stages involved in the programming and design of the software for processing and analysing the ECG signal are demonstrated in Figure 7. The main function of the software is to further process the ECG signal through filtering stages, extract and analysis all the features of the ECG signal so that the user is able to view the ECG tracing showing all the automatically measured components of the ECG.
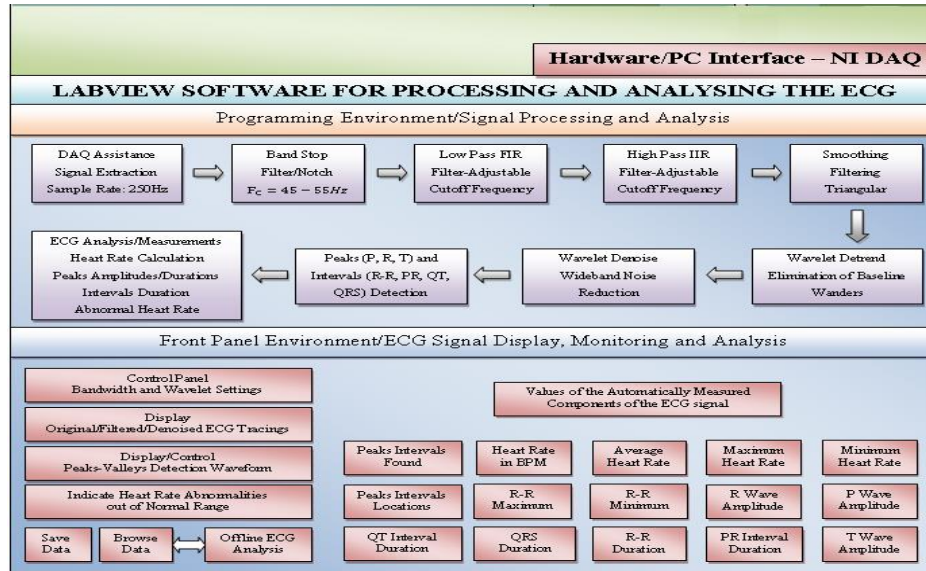

Figure 7: Flowchart of the software environment

The Flowchart shown in Figure 7, represents the functionality of the software which is programmed to remove (first stage) the power line interference and wideband noises that might still exist in the ECG signal and also remove the baseline wandering which cannot be removed from the hardware so that the signal is sufficiently clean for accurate detection and measurement of its features by the software. The software is separated into two environments: The programming environment and the front panel environment. The programming environment includes the signal processing, the ECG feature detection, the signal analysis, measurements and calculations of all the components of the ECG signal. The front panel environment is designed so that the user is able to view, monitor and analyse the ECG tracings and includes the display of the ECG tracings in real time and offline monitoring, the settings for controlling the signal processing and analysis, the display panel for tracking and indicating the values of all the automatically measured features of the ECG signal as well as Heart Rate abnormalities.

The hardware/PC interface is achieved with the use of the DAQ device which sends the amplified and filtered ECG signal to the PC through its analogue inputs, where LABVIEW software programming environment is used and developed for further processing, displaying and analysing the ECG signal. In order to process the ECG signal, the first step in the programming of the software is the acquisition of the ECG data from the DAQ device into the software. This task is performed by the DAQ assistant function from which the input of the DAQ device (which is connected to the output of the ECG hardware) is selected as well as the sample rate.

The next stage includes a series of different digital filters for removing power line interference and wideband noises that might still exist in the ECG signal. A band-stop filter with band cutoff at 45Hz to 55Hz is used for totally eliminating 50Hz power line interference that might still interfere with the ECG signal. The next stage consists of a low and a high pass digital filters with adjustable cutoff frequencies in order to control and set the desired bandwidth for either monitoring or clinical recordings and eliminate unwanted interfering signals. Furthermore, a smoothing digital filter is used to remove high frequencies and smooth the ECG signal and pass it to the wavelet Detrend function. Wavelet transform approach is used to remove the low-frequency trend of the ECG signal and baseline wandering in order to achieve accurate detection and measurement of the ECG components. Moreover, wideband noises are totally eliminated by the wavelet Denoise VI before the signal passes to the detection stage. After processing the ECG signal and removing all the unwanted high and low-frequency components, all the features of the ECG signal are detected and measured. In this stage, all the peaks and valleys of the ECG signal are detected and at the same time, their amplitudes and durations are measured and sent to the front panel. The front panel environment is designed in order for the user to view and analyse the ECG tracings in real time and gives the values of all the automatically calculated components of the ECG signal. The front panel includes several X-Y Waveform Graphs for displaying the ECG tracings at each step of the signal processing on which the ECG tracing moves along the axis.

It displays the original ECG as acquired from the ECG hardware prior to digital filtering. After digital filtering and removing baseline wandering the waveform with detected features can be seen. Furthermore, it includes a control panel containing all the settings that can be performed during the processing of the signal such as bandwidth settings, trend level settings, wavelet settings, etc. The settings can be

changed prior and/or during the recording of the ECG signal. This environment also includes a panel on which all the automatically calculated values of the ECG components are displayed during the recording. It includes a save button which allows the user to save the ECG data to a file in order to use them at a later stage for offline analysis without the need to reconnect the patient to the device.

VIII. RESULTS AND DISCUSSION

The experimental setup involved connecting the patient to the isolated side of the hardware and the connection of each circuit stages to the DAQ device in order to send the ECG data to the PC and obtain their functionality. The block diagram of the experimental setup is shown in Figure 8, i.e. the ECG tracings will be taken from the output of each of the hardware stages by connecting them to the DAQ device connected to the PC while the subject is connected to the isolated side of the circuit in order to obtain the performance of each stage. The ECG tracings will be displayed in the Front Panel Environment of the Software together with the automatically measured components of the ECG.
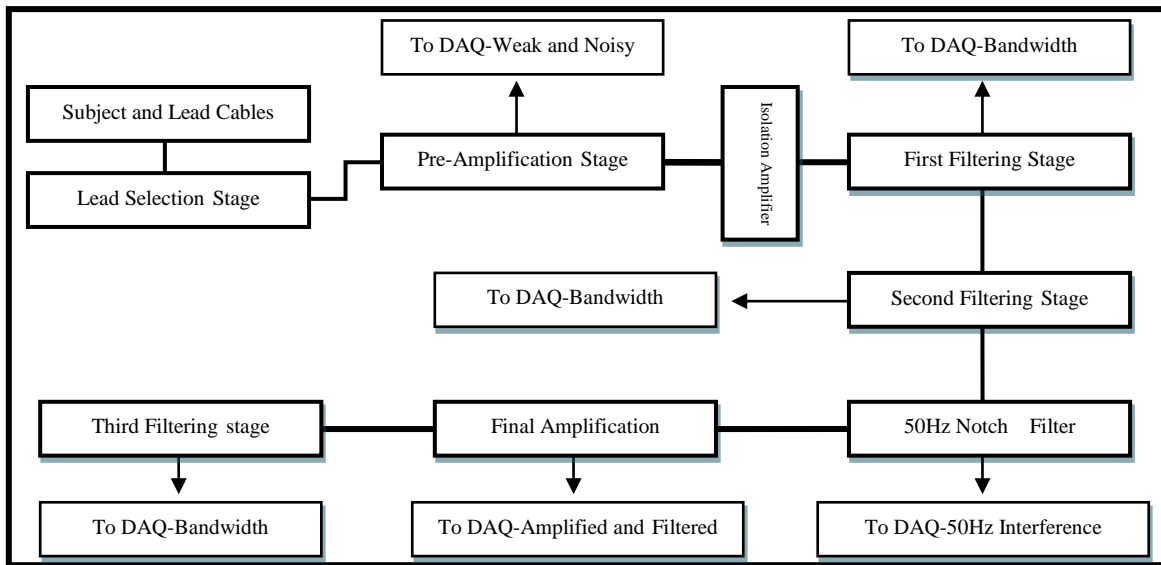

Figure 8: Block diagram of the experimental setup

The first step in setting up the experiment is to connect the lead cables to the inputs of the lead selection stage with their common shield connected to the ground of the hardware. Then the output of each of the hardware stages is connected to the analogue inputs of the DAQ device which is connected to the PC in order to send the ECG recording to LabVIEW for processing and analysis. Then the two 9V batteries are placed within the battery holder which has its terminals connected in series in order to achieve a ±9V dual supply. The practical experimental setup is illustrated in Figure 9.

Figure 9: Practical experimental setup

Secondly, the electrodes are placed on the subject limbs with the left and right arm electrodes placed on the inside of the subjects wrists while the reference right leg electrode and the left leg electrode placed near the ankles. Measurements are then taken using Lead I system while the subject is seated in a relaxed manner as shown in Figure 10.

Figure 10: Lead I ECG recording

The final low pass filter with high cut off frequency (above 50Hz) highly attenuated the 50Hz power line interference and other wideband noises, leaving all the features of the ECG signal intact to be processed and analysed by the software. The ECG tracing in Figure 11 is obtained from the hardware's output at 0.03Hz to 50Hz bandwidth which verifies that the constructed ECG hardware is capable of producing clean and diagnosable ECG tracings without the influence of noises and artefacts containing all the features of a standard bipolar ECG recording. Such a clean ECG tracing with minimum possible noise will contribute to the accurate extraction and analysis of all its features by the software.

Figure 11: ECG tracing acquired from the output of the hardware's final filtering stage

The detrended or denoised ECG tracing is displayed on a waveform graph which auto scales both of its axis depending on the amplitude and duration of the signal as illustrated in Figure 12 so as the user is able to view and easily measure all the waves and intervals of the ECG tracing.
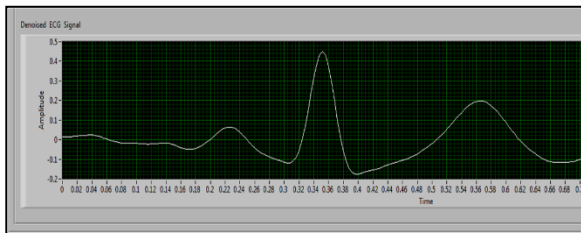

Figure 12: Detrended/denoised ECG tracing

The Wavelet Detrended/Denoised functions are used at the final stage of the ECG processing in order to remove baseline wandering and other wideband noises before extracting and analysing the ECG features. It is essential to remove baseline wanders and wideband noises at this stage bringing the ECG baseline to zero voltage in order for the program to be able to accurately detect and measure all the waves and intervals of the ECG.

After ensuring the accurate performance of the program's signal processing stage, the performance of the detection and analysis stage is tested. In order to calculate the Heart Rate of the subject and measure all the features of the ECG signal, a detection and analysis program was created in LabVIEW programming environment. As can be seen from Figure 13, the created program for detecting the R-R intervals accurately functions since it detects and highlights all the R waves appearing in the waveform graph.
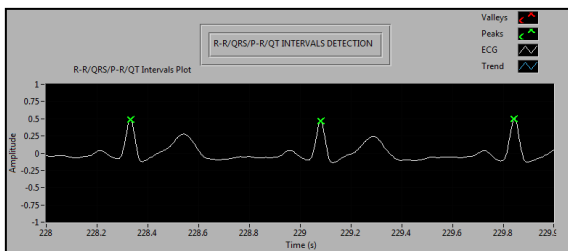

Figure 13: R wave detection

After detecting the R waves, the program automatically measures the R-R intervals and uses this value in order to calculate the Heart Rate in BPM. In addition, it plots the Heart Rate history based on previously calculated heart rates.

In addition, the software is capable of accurately detecting all the valleys of the ECG signal as can be verified from Figure 14, in order to measure the duration of the waves and intervals.
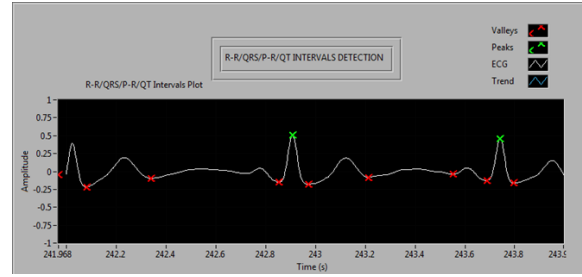

Figure 14: Detection of the ECG valleys by the software

This is achieved by using the wavelet peaks/valleys detection express VI which detects any peaks and valleys from the ECG signal depending on the trend level used. In order to detect and further measure the duration of the waves and intervals the trend level was set at -0.002. This level is accurate enough for detecting only the necessary points below that number. However, in cases of an abnormal ECG tracing from which the valleys or peaks cannot be detected by using this trend level, a different trend level can be used by changing it from the control panel.

Having detected the peaks and valleys, the program automatically calculates their amplitudes and durations and displays their values in a measurement section.

The next section of the program includes only the detection and measurement of the QRS complex. After testing this section, it can be observed that it accurately detects and measures the QRS complexes as can be seen from Figure 15. In this case, the QRS duration is measured by the software to be 0.07 indicating a normal QRS duration. The detection of the QRS complex depends on the trend level used by the user. The blue line on the graph represents the trend level for detecting the valleys. The user can move this line along the Y axis in order to detect the required valleys that exist below the trend level. In this case, the trend level set at around -0.02 in order to detect and measure only the QRS duration.
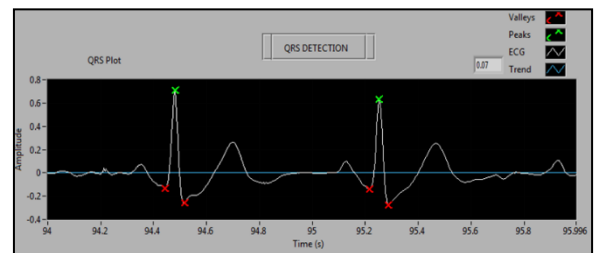

Figure 15: Detection and measurement of the QRS complex

The next section of the software programming involved the detection and measurements of the ECG waves. During simulation, it was observed that this section of the program accurately detects and measures the amplitudes of the waves as can be seen from Figure 16.
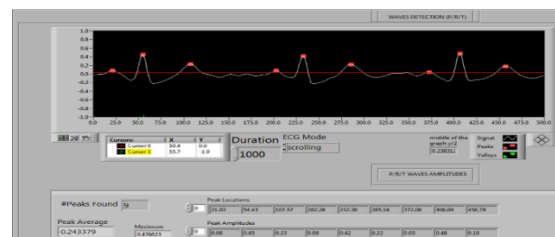

Figure 16: Detection and measurement of the ECG waves

Depending on the trend level (red line) used, the software detects and highlights all the waves above this level and at the same time, it automatically calculates and displays their amplitudes below the graph. The user can detect the required waves by scrolling and place the trend level line below the peaks under investigation so that all the detected peaks are above the line. The software displays the number of the peaks found each time, their locations on the graph as well as their amplitudes. From Figure 16 above, the amplitude of the P wave was calculated to be 0.08mV, the amplitude of the R wave 0.45mV and the amplitude of the T wave 0.23mV indicating normal wave amplitudes.

All the values of the ECG components are summarised and displayed in the ECG measurement section of the front panel environment which indicates either normal or abnormal heart conditions. Figure 17 illustrates the ECG measurement section of the front panel environment. In cases where the average heart rate of the subject is outside the normal range (60 to 100 BPM) the green light indicator at the top of the section turns on indicating a heart rate abnormality. In this case, the light indicator is off since the average heart rate is 79.72 beats per minute (BPM) indicating a normal heartbeat.
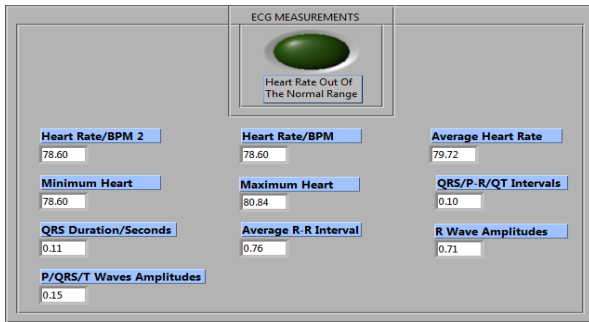

Figure 17: ECG measurement section

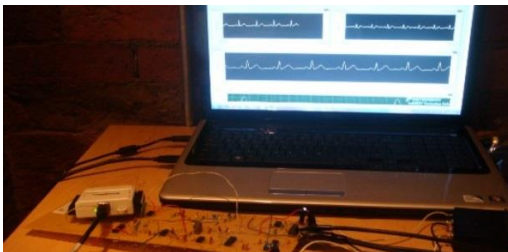Figure 18 illustrates the overall ECG system during operation.

Figure 18: Overall ECG system operation

For cases that the user wishes to further analyse the ECG tracing without having the patient reconnected to the device, an offline ECG analysis section was also created. The user can save the ECG data during the real-time recording and then press the read data from the measurement file button so that the saved ECG data can be plotted on the offline ECG analysis graph.

IX. CONCLUSION

A prototype of a Single Channel 3-Lead Electrocardiograph was successfully designed and constructed which processed the differential potentials accurately and provided the ECG recordings accordingly. Additionally, a software-based processing environment was developed receiving the pre-processed ECG data via the hardware and then provided accurate measurements of all the features of the ECG signal. The ECG system, therefore, consisted of the combined hardware and software-based environment with some advantages including electrical isolation, selection and recordings of all the standard bipolar leads, selection between monitoring and ECG recordings and the automatic detection and measurements of all the features of the ECG signal.

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